Gravitational waves-- a new window on the universe

LIGO--Laser Interferometer Gravitational Wave Observatory

Jay Marx
LIGO Laboratory
Caltech

LBNL Nuclear Sciences
Division Colloquium
December 7, 2011

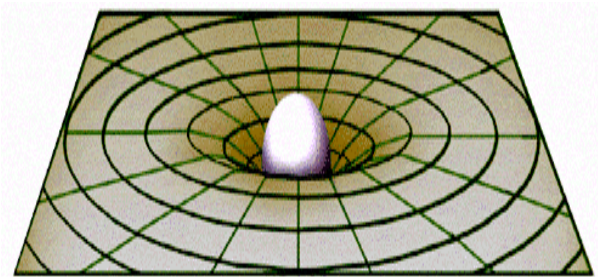
LIGO-G1101222

Topics

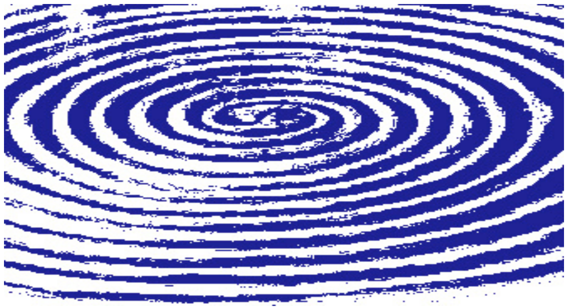
- *About gravitational waves*
    - *Characteristics of GWs*
    - *Astrophysical sources of GWs*
- *LIGO-- observatory for GWs from astronomical sources*
    - *What is LIGO and how does it work*
    - *Status of LIGO and recent scientific results*
    - *Evolution of LIGO over the next decade*
- *Gravitational wave astronomy– a new window on the universe*

Gravitational waves

- GR- The fabric of space-time is dynamic
  - » Mass causes fabric to warp and in some circumstances to ripple

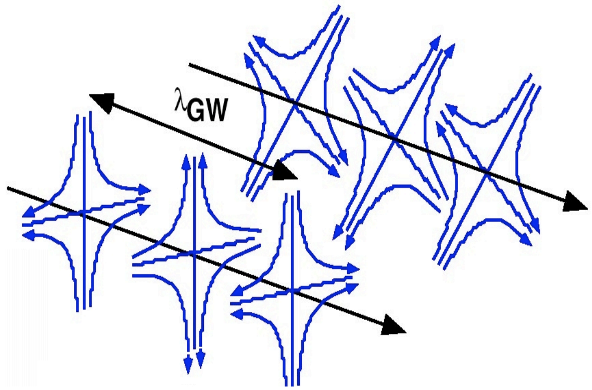


- GWs are the ripples in the fabric of space-time that propagate at light speed

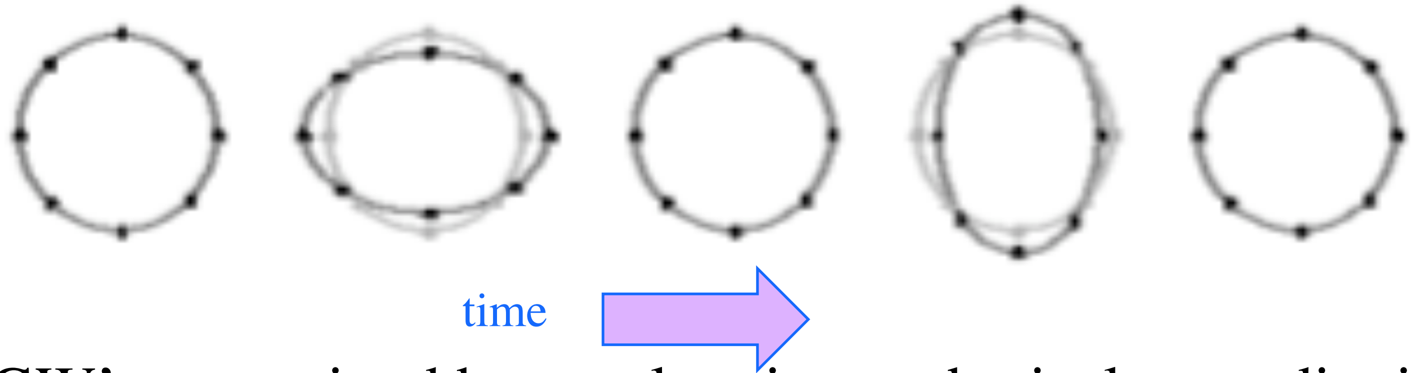


Gravitational waves

- Because GR is a tensor theory GWs are transverse, quadrupole waves with 2 polarizations.

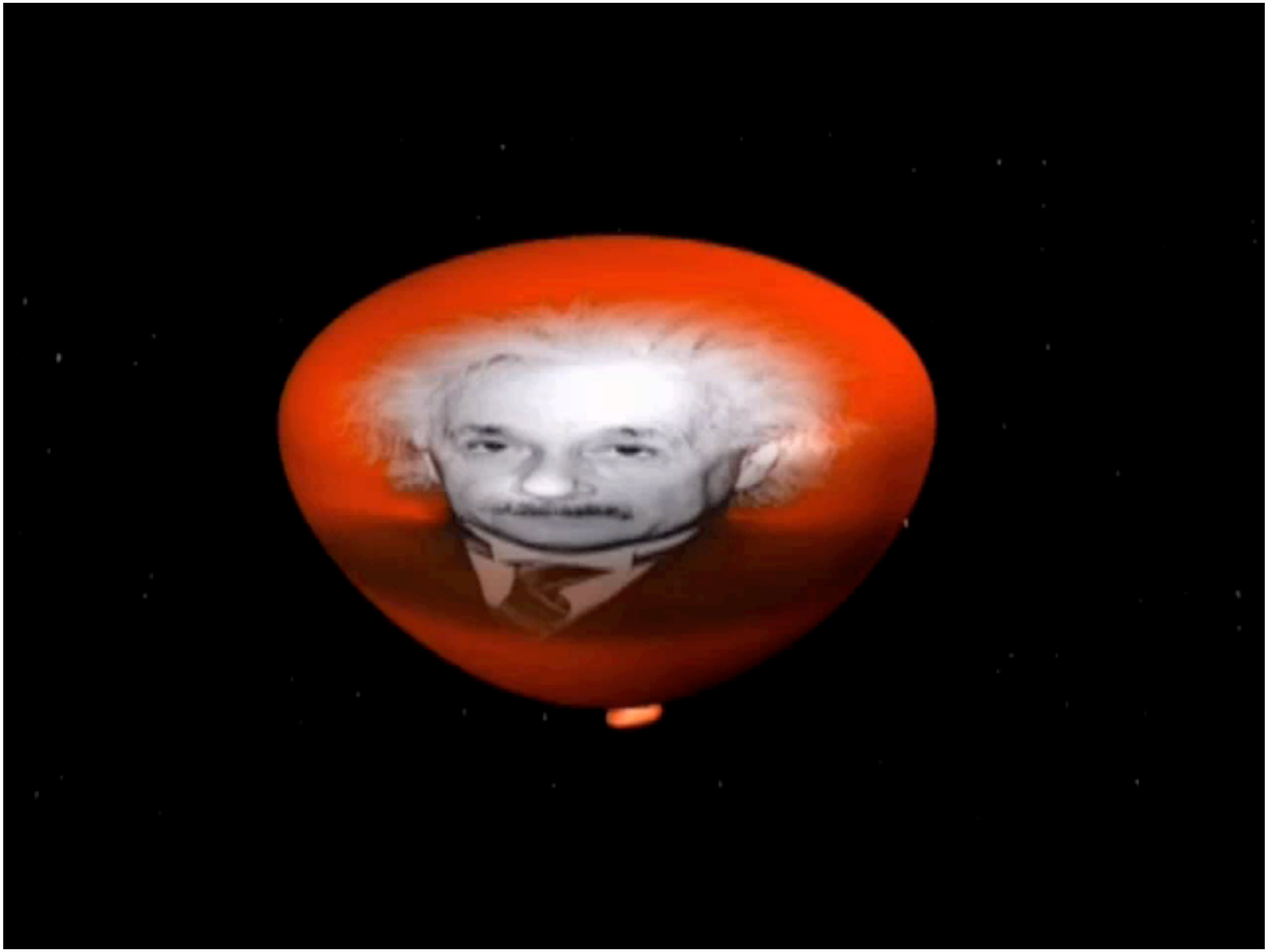


- ***Gravitational waves stretch/squeeze space and everything in it transverse to direction of propagation. The key to detecting them.***



- GW's are emitted by accelerating aspherical mass distributions

A GW traveling into the screen

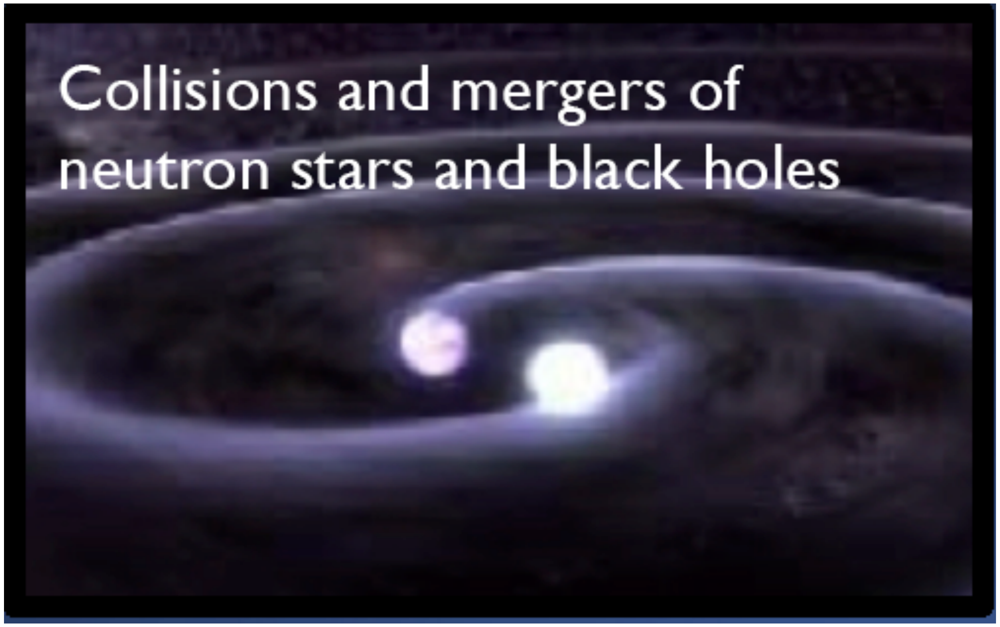


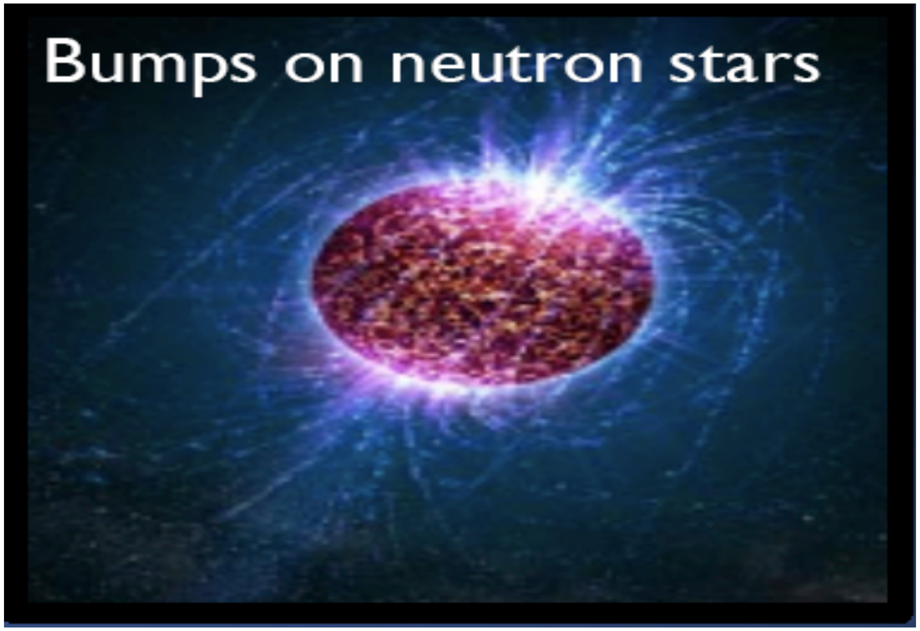
GWs carry very different information about source than EM radiation

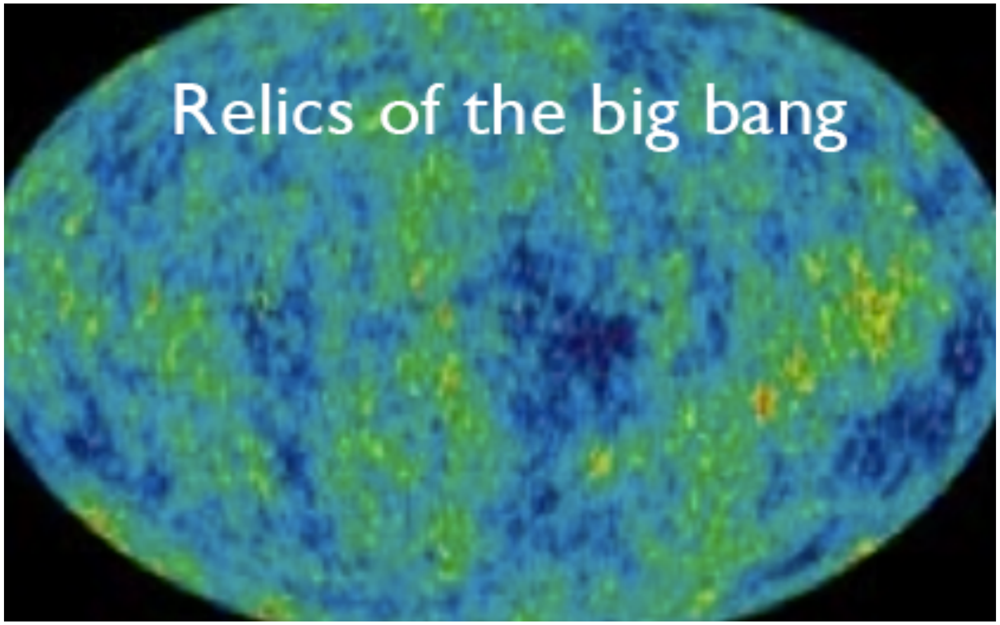
- **EM radiation emitted by moving electric charges**
  - Emitted in small regions with short wavelength
  - Carries information about small portion of astronomical source (that's why can image source with EM)
  - Can be absorbed/distorted in transit by intervening matter

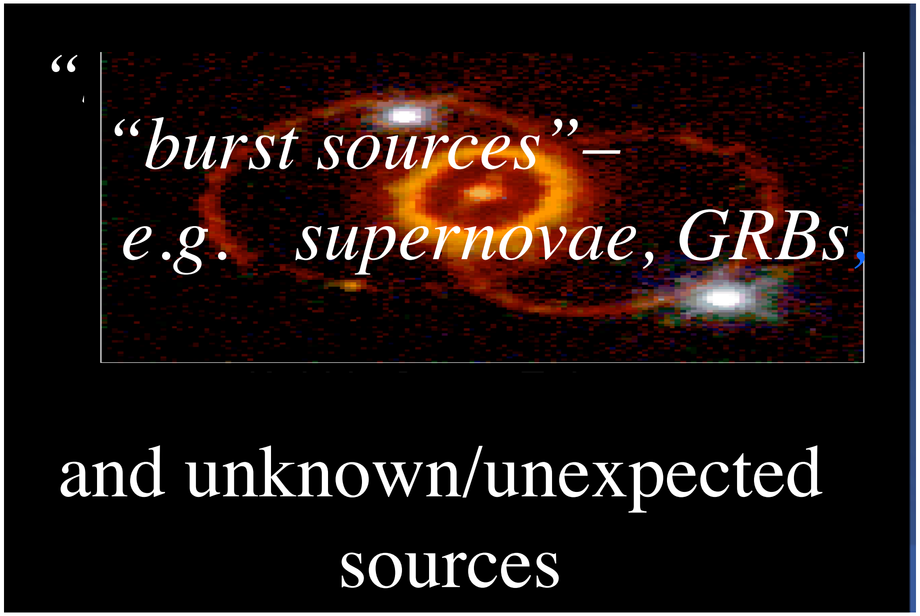
- **GWs are emitted due to motion of overall mass of entire system**
  - For astronomical systems GWs have long wavelengths comparable to size of system
  - Convey information about the motion of large-scale mass distributions- gives a "picture" of the dynamics of an astronomical system
  - Because gravity is weak, GWs travel ~unimpeded from source core

GWs--ripples in space-time from some of natures most violent events

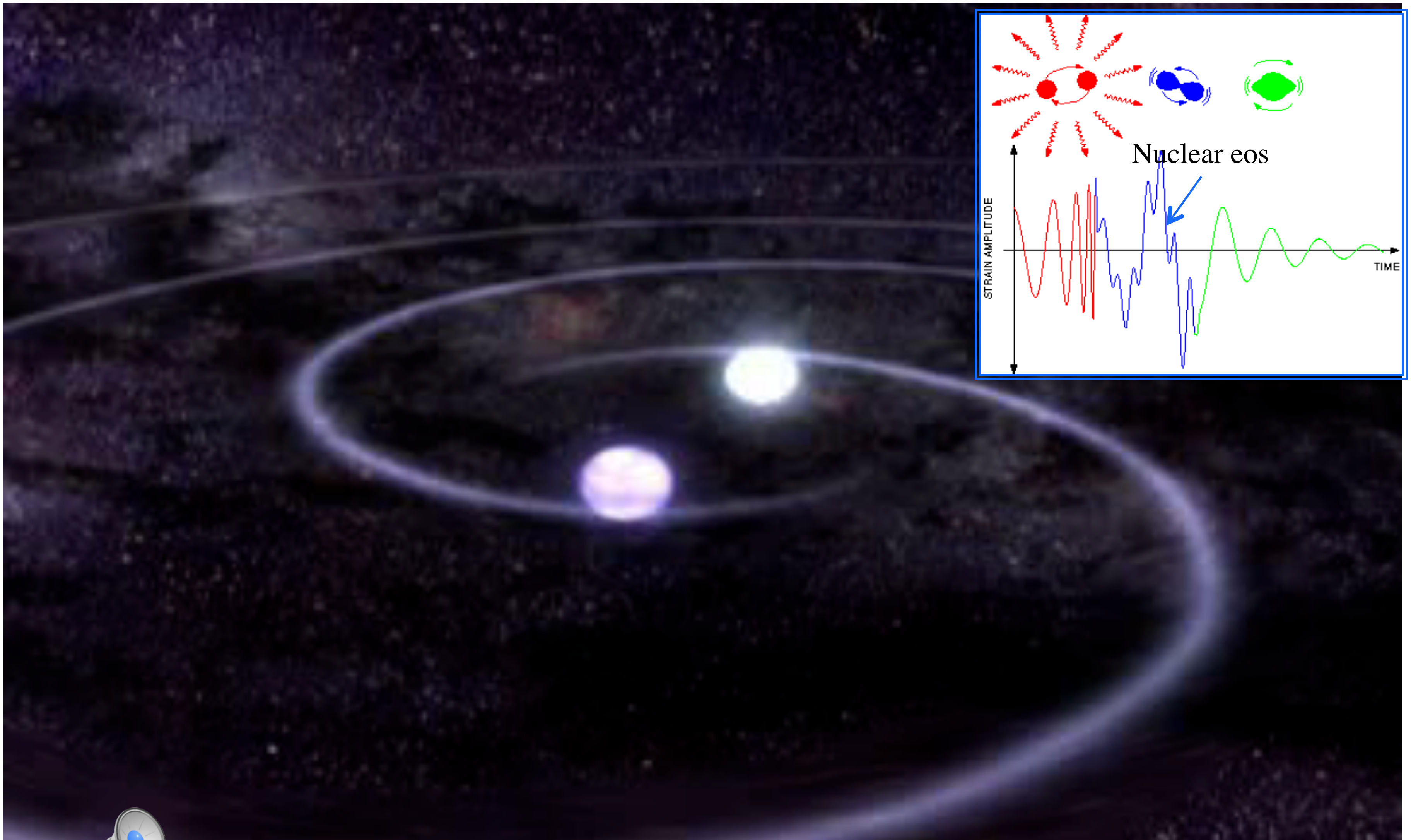








GWs from NS-NS inspiral & merger



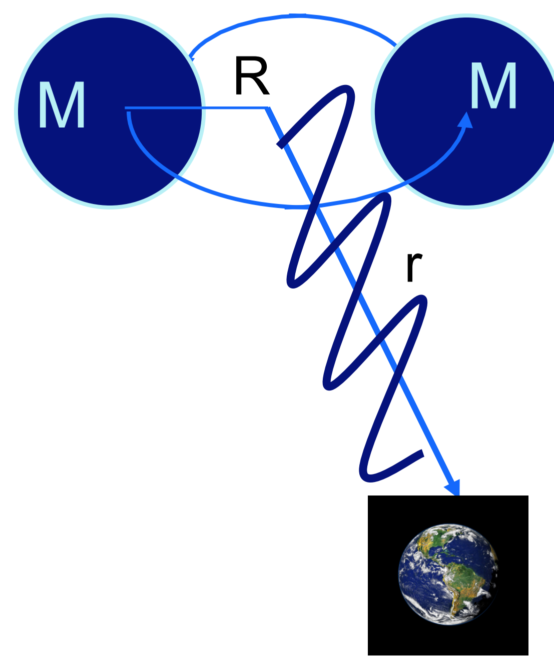
Strength of Gravitational Waves
e.g. from merging neutron stars

~ 50 million light years away

- Gravitational wave strain (strain h= △L/L)

"h" is relative stretch/squeeze of fabric of space over a distance L due to a passing gravitational wave

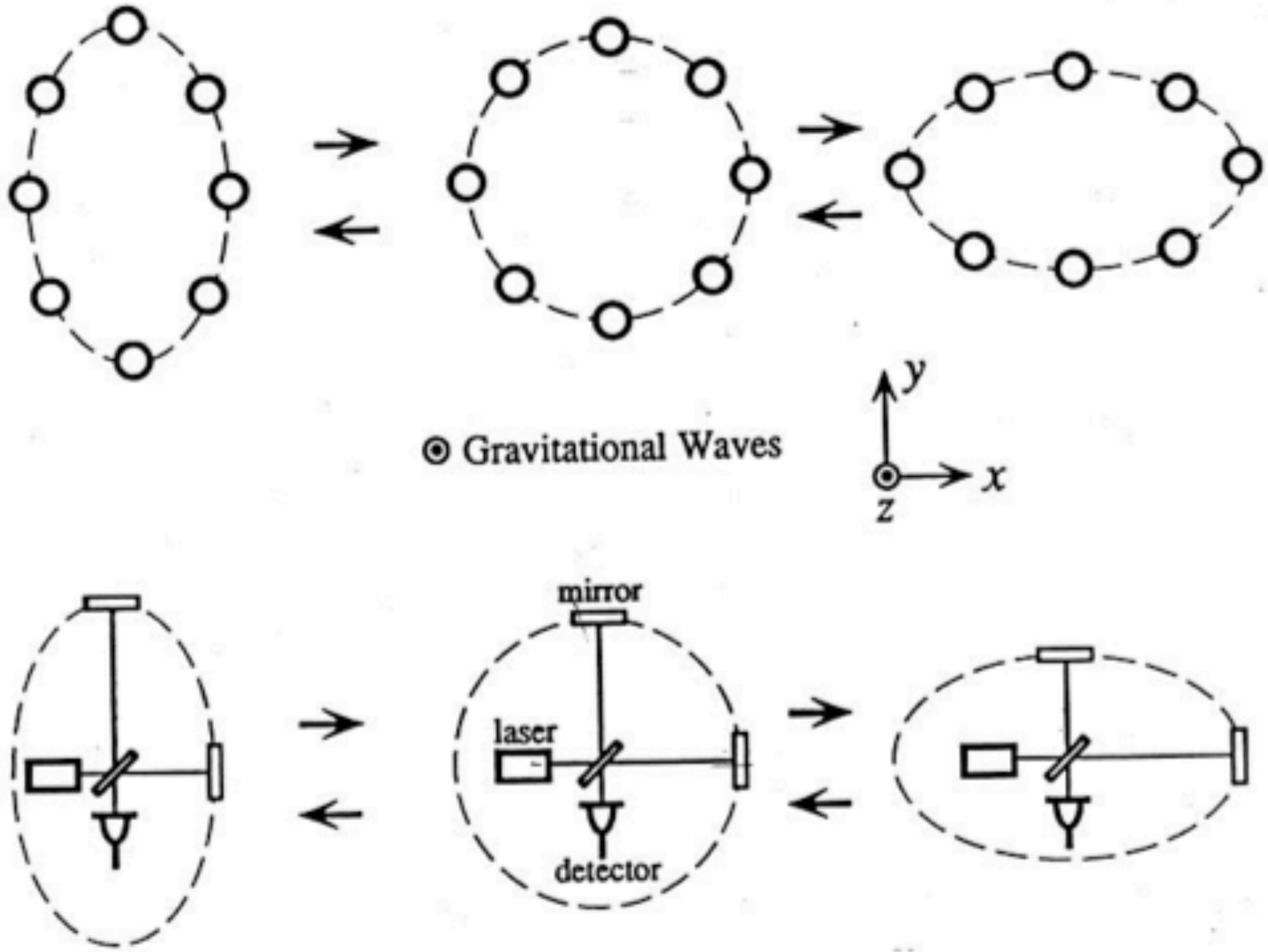
Einstein-- $h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow$ $\boxed{h \sim 10^{-21}}$



If the distance to the nearest stars is stretched by a factor of 10^{-21} this corresponds to width of a human hair

The tiny size of the effect of a GW sets the challenge for LIGO

Gravitational waves can be seen with an instrument sensitive to changes in length



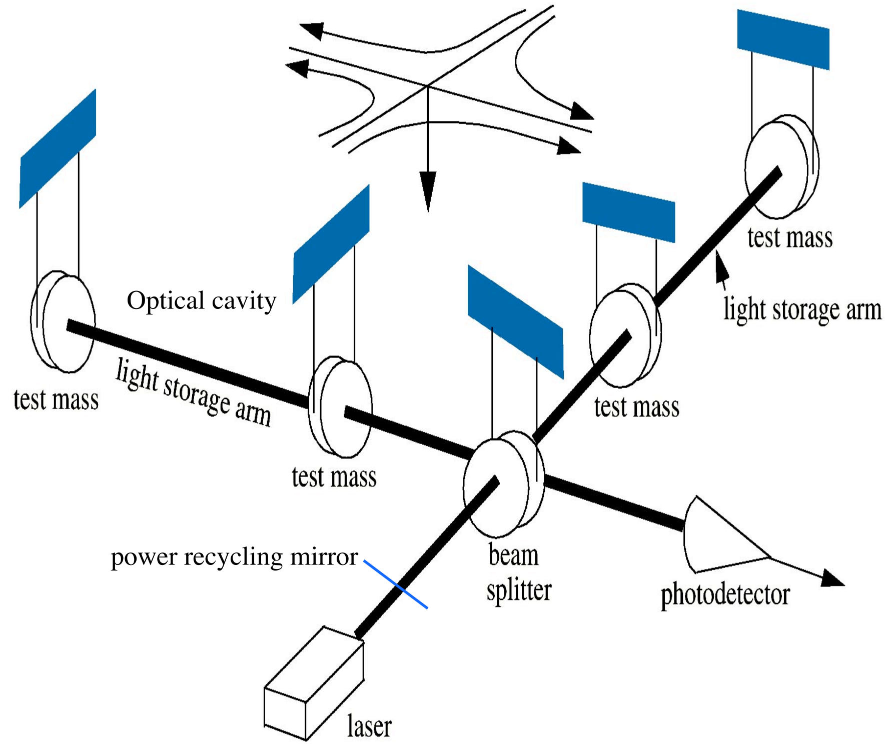
Detecting GWs with Precision Interferometry

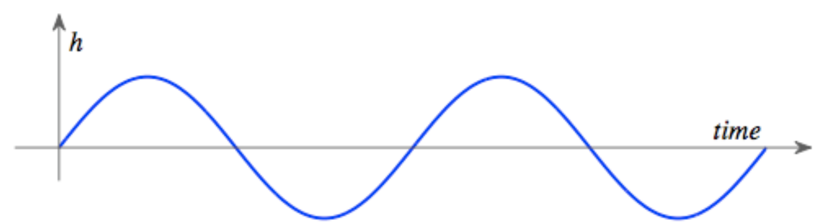
- Suspended mirrors in L-shaped configuration act as markers of points in the fabric of space/time

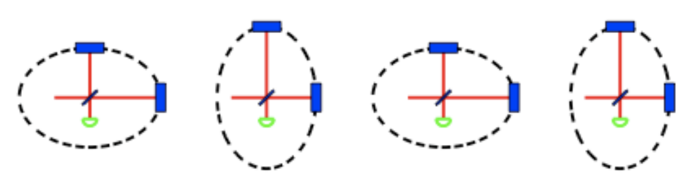
- A passing gravitational wave alternately stretches (compresses) space-time thus changing the relative separation of the mirrors in each arm

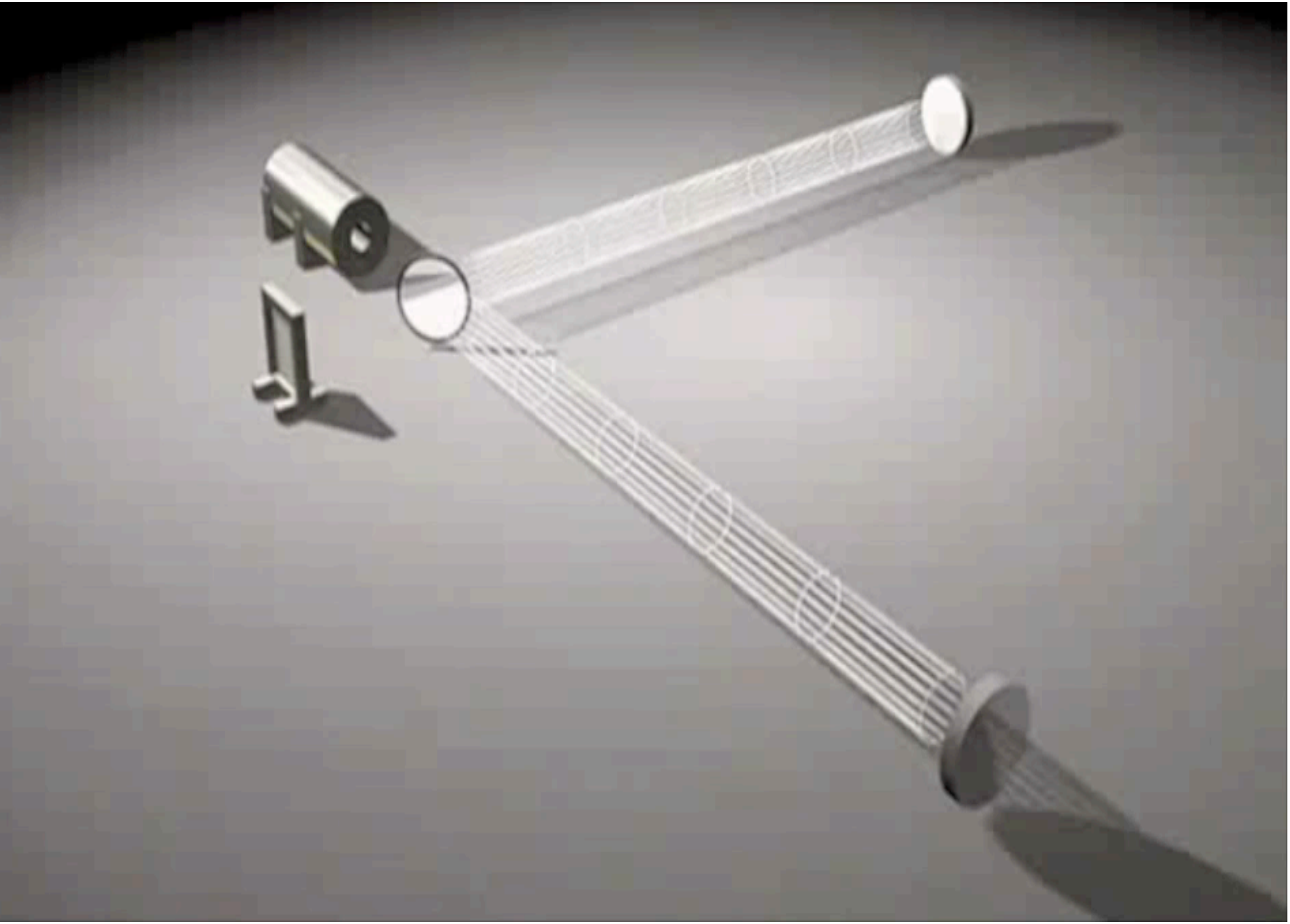
- Optical interferometery is used to measure relative separation between mirrors in each arm

The wavelength of light (~1 millionth of a meter) is the yardstick to measure mirror separation









The experimental challenge for LIGO

Remember h = 10^{-21}? $h = \Delta L / L$

The strain from a GW from a neutron star pair merging 50 million light years away

For *LIGO the length of the arms of the interferometer is* L= 4 km

So if h=10^{-21}, with arm length of L=4 km
the effect of the GW is to change the distance between mirrors by:

$\boxed{\triangle L \sim 4 \times 10^{-18} \text{ meters!!!}}$

What makes building a GW detector so hard?

The challenge: measure the relative distance of mirrors in 4 km interferometers arms to accuracy ~10^{-18} m;

~ 1/1000 the size of a proton!!!!

- **So must understand and control anything that can jiggle the mirrors, noise and other effects that could mimic gravitational waves at the 10^{-18} m scale in kilometer-scale instruments**

Is it even possible to reach the needed sensitivity?

Intrinsic resolution of interferometers- how accurately can a fringe be split?

It's counting statistics-- sqrt of number of photons during measurement

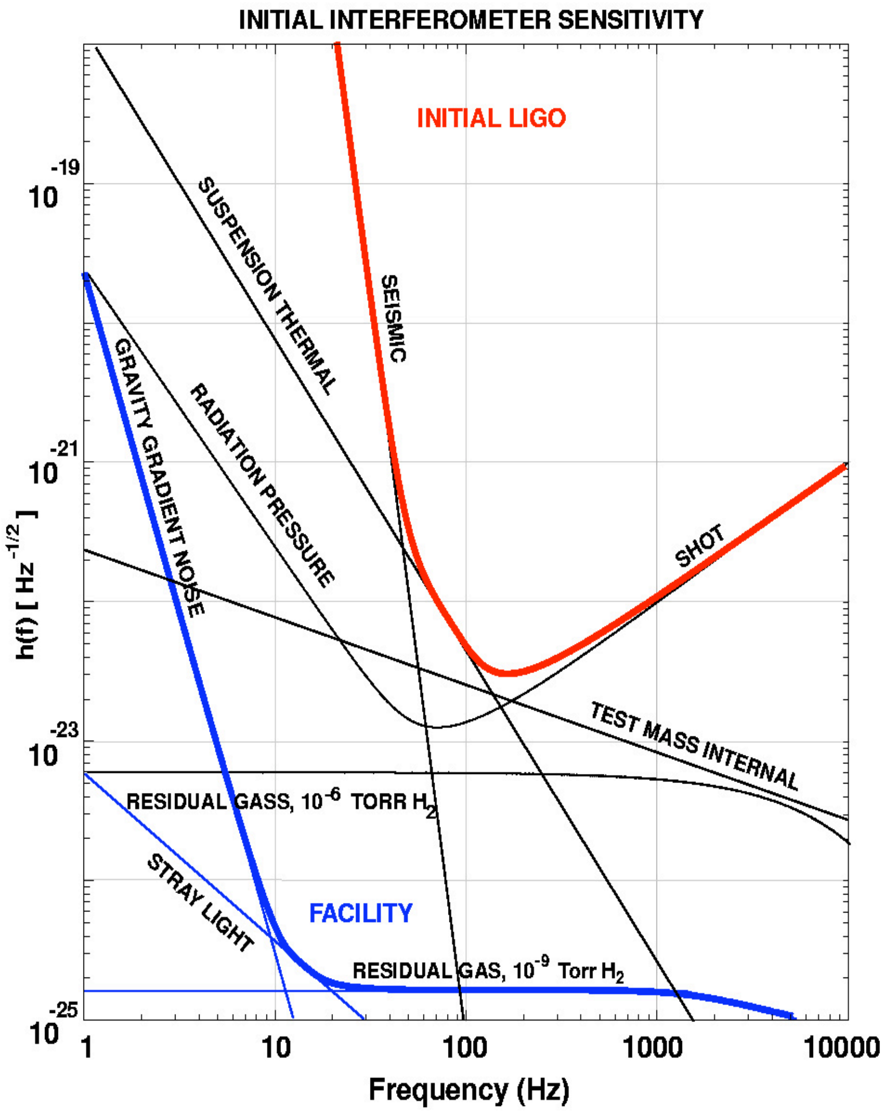
- *10^{21} photons/second at beam splitter where interference occurs*
- *Measurement time ~10^{-2} seconds (at 100 Hz)*
- *Effective arm length = 4 km * average number passes for each photon*
  (Fabry-Parot arm cavities--- b~50)

1 x 10^{-6} cm

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb\sqrt{\dot{N}\tau}} =$$

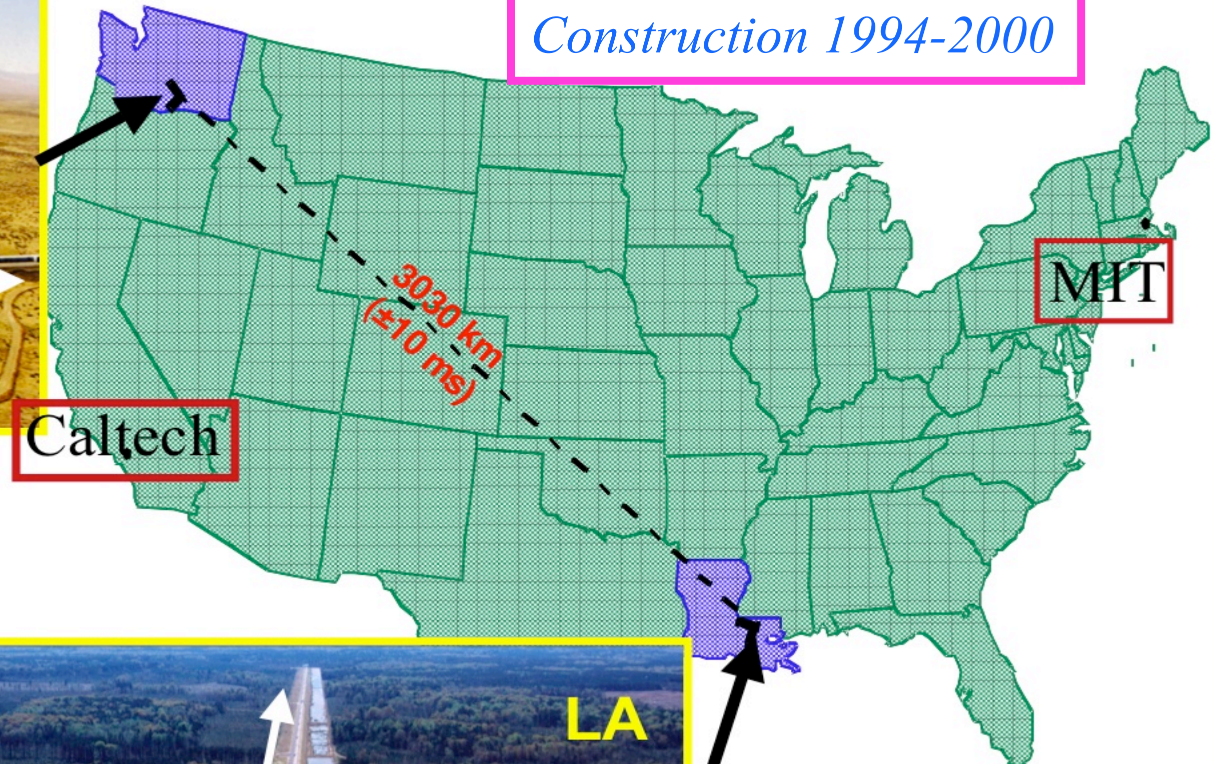
$h = 6x10^{-22}$ at 100 Hz

Major noise sources must be under control



- Displacement Noise
  - » Seismic motion (limit at low frequencies)
    - – Ground motion from natural and anthropogenic sources
  - » Thermal Noise (limit at mid-frequencies)
    - – vibrations due to finite temperature
  - » Radiation Pressure
- Sensing Noise (limit at high frequency)
  - » Photon Shot Noise
    - – quantum fluctuations in the number of photons detected
- Facilities limits
  - » Residual Gas (scattering)
- Inherent limit on ground
  - » Gravity gradient noise
- Technical noise-
  - » laser, control, electronics, etc

LIGO Laser Interferometer Gravitational-wave Observatory



Construction 1994-2000

- **Managed and operated by Caltech & MIT with funding from NSF**
- **LIGO Scientific collaboration- 800 members & 60 institutions, world-wide**

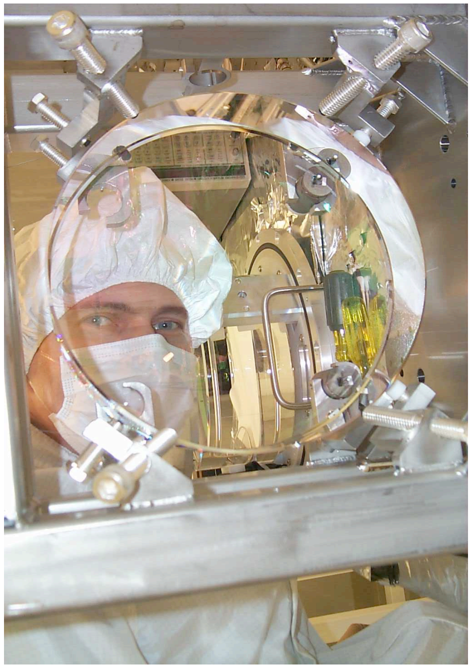
2 widely separated sites so not fooled by local disturbances

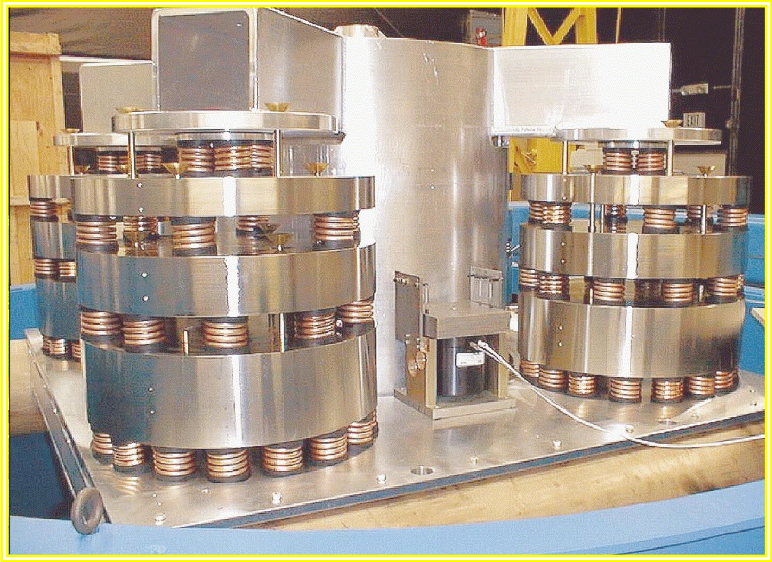
16

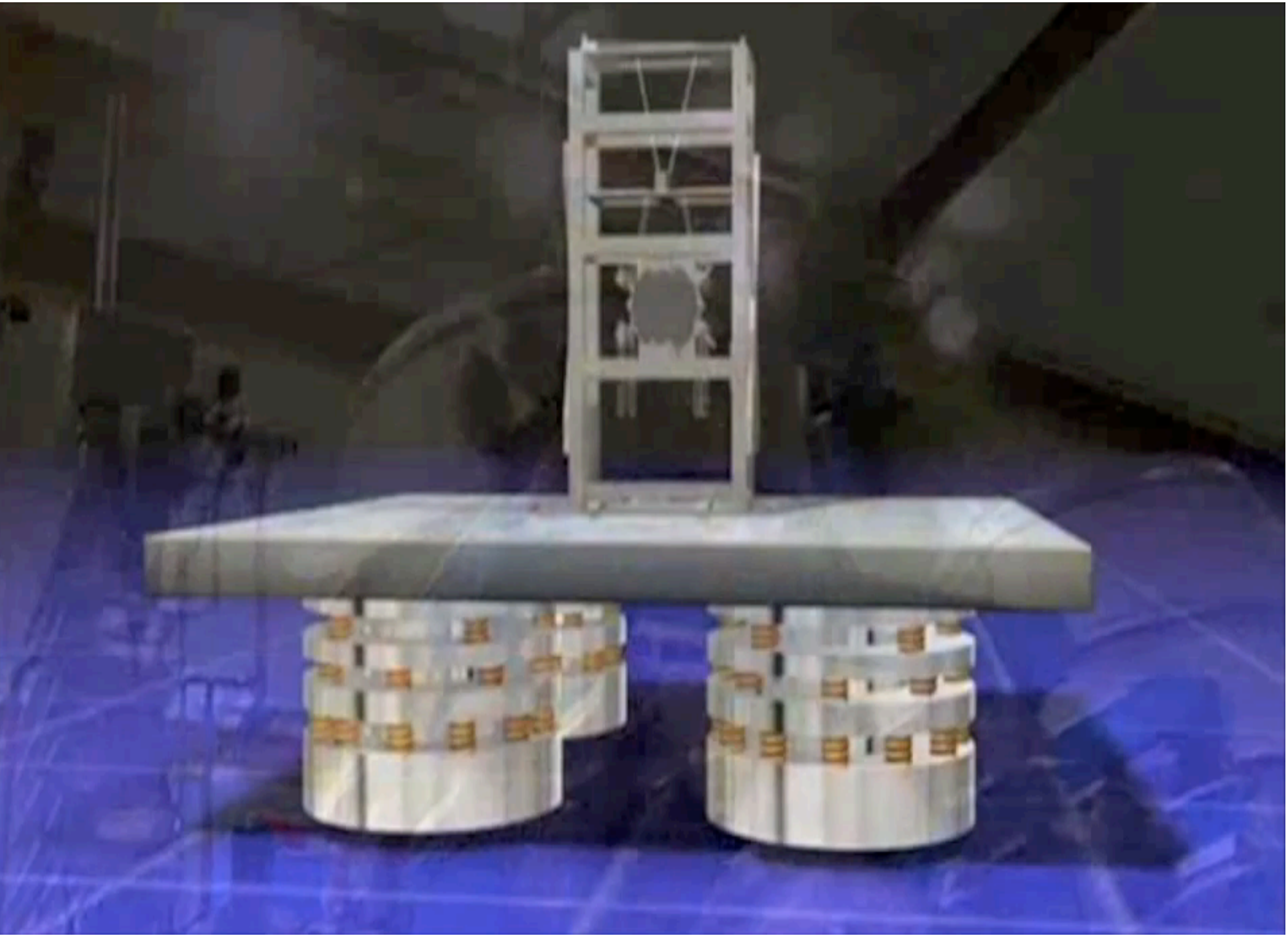
Hanford
Washington

Livingston
Louisiana

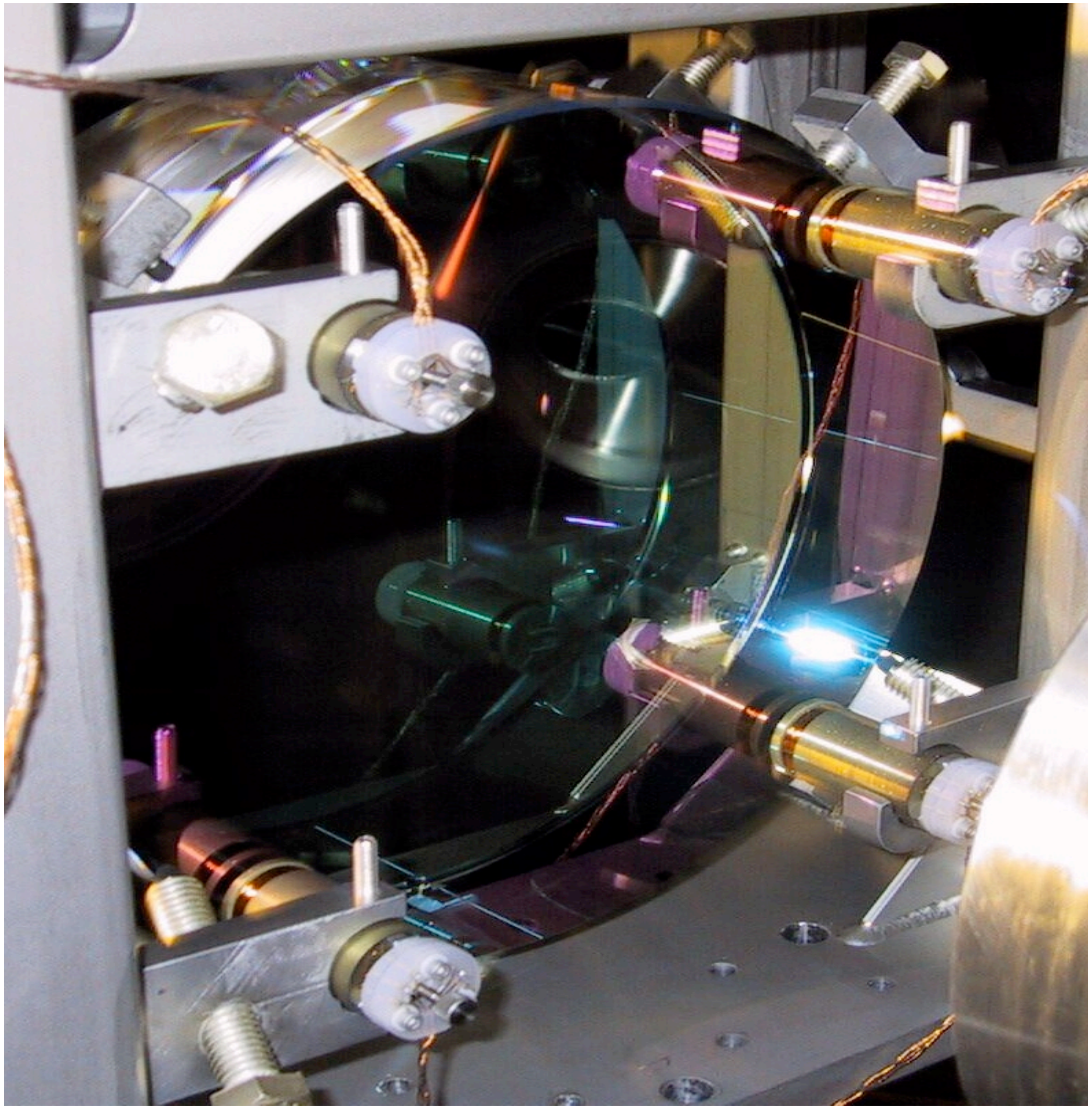
Some initial LIGO hardware







Mirror and control actuators

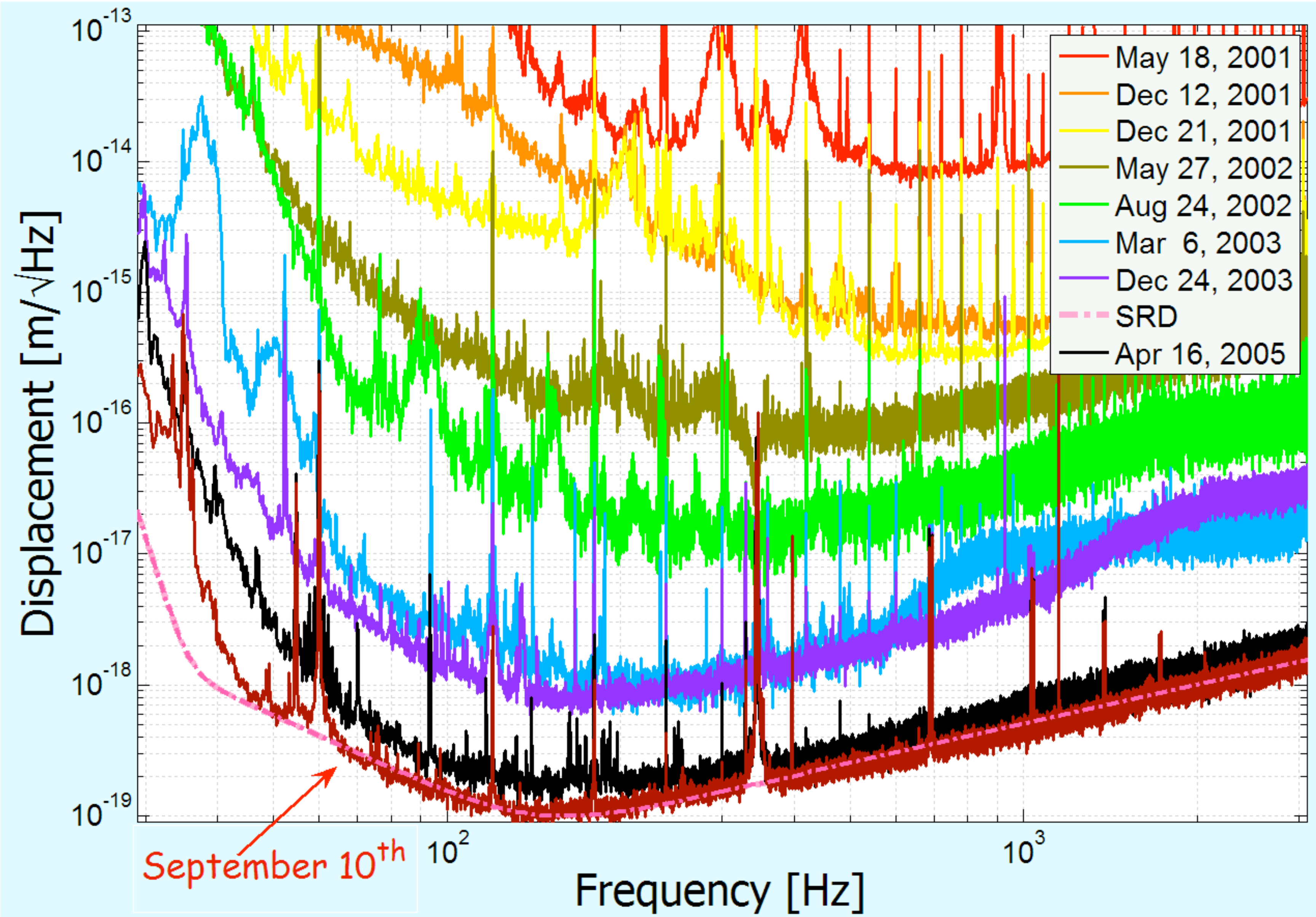


How to we avoid being fooled?

- **Monitor everything that can fake a GW signal**
  - » Ground motion (with seismometers)
  - » Line voltage
  - » Acoustic noise (mircophones)
  - » Magnetic fields
  - » Etc.
- **Require at least 2 independent signals**
  - » e.g. 2 inteferometers, 2000 miles apart
  - » Interferometer + external trigger (e.g. optical supernova)
- Many other checks of reality of a signal—

  e.g blind signal injections

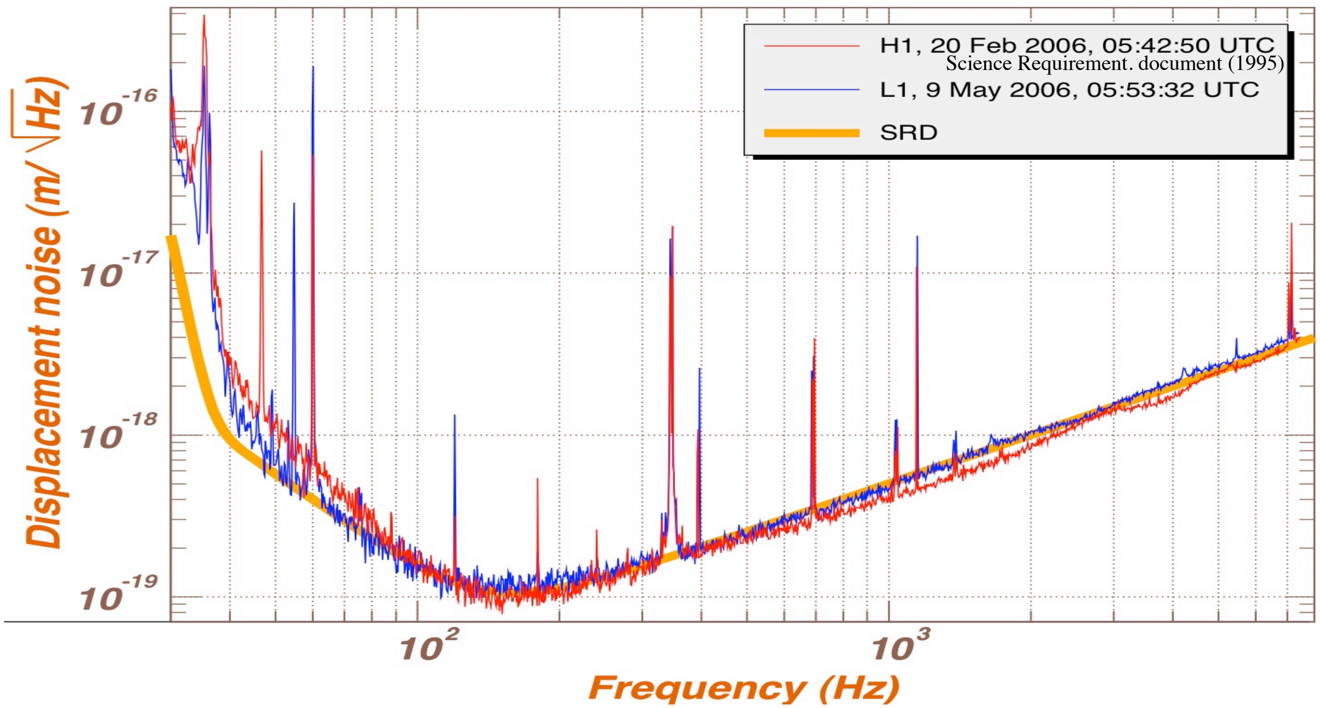
2000-2005: The challenge of taming the interferometers



Meeting the experimental challenge

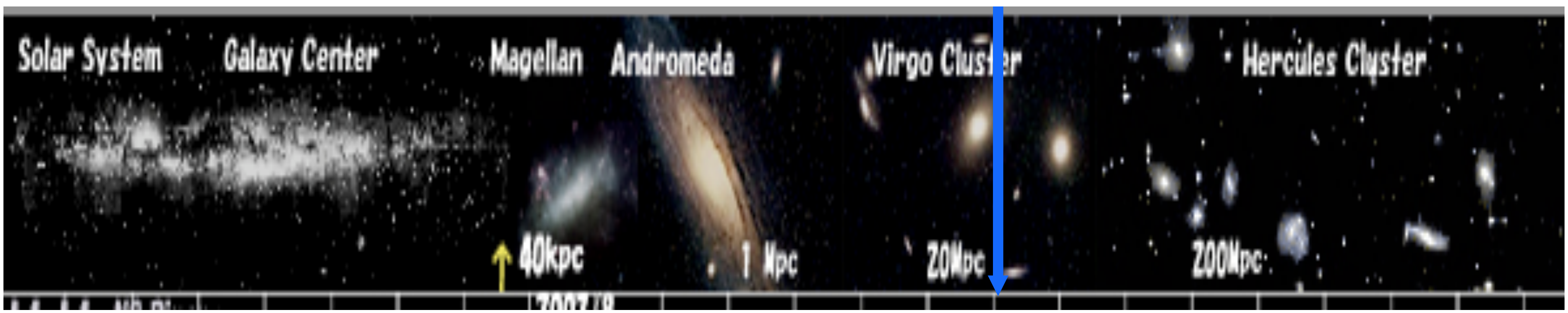
- **In 2005 after 5 years of intense effort the predicted sensitivity was reached--LIGO could measure 10^{-18}m**

- **LIGO was ready to begin the serious search for GWs**



LIGO's evolution after reaching design sensitivity

- **Initial phase- search for gravitational waves**
  - » **November 2005 to October 2007**
    - –Successful 2 year long science run at design sensitivity
    - –Hundreds of galaxies in range of LIGO
    - –Would see merging neutron star binaries as far as 100 million light-years from earth



–Data analyzed, science results published

Data analysis

Data analysis from 3 interferometers by the LIGO/Virgo (Italian/French instrument near PISA) collaboration is organized into four types of search analyses:

1. Binary coalescences (“inspiraling” NS-NS, BH-BH or NS-BH pairs)

   - Signal shape matched to well modeled chirped waveforms

2. Transients sources with unmodeled waveforms (“bursts “)

   - High S/N in coincidence with external trigger or between LIGO sites

3. Continuous wave sources (“GW pulsars”)-

   - GW signal phased to known pulsar ephemeris after Doppler correction

4. Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

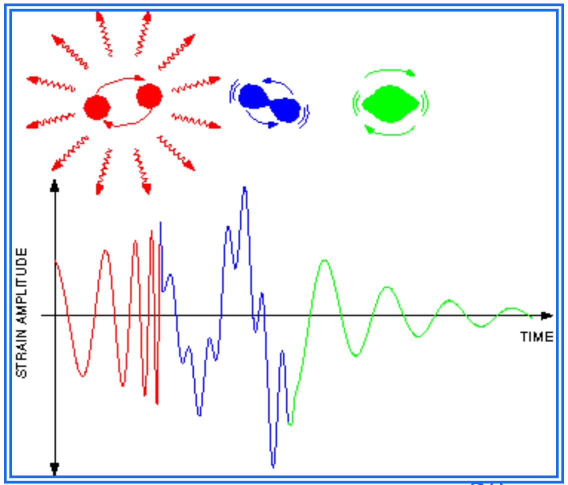
   - Stochastic signal correlated between multiple interferometers

Sample of science results from LIGO

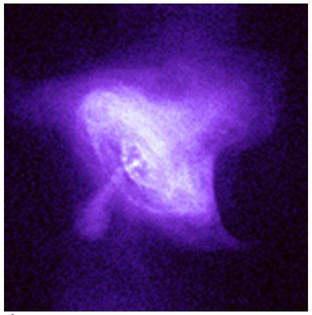
- **No GW observed yet --- not unexpected -- odds ~few % with initial LIGO sensitivity**

- **Data set scientifically meaningful upper limits on numbers or strength of cosmic sources**

- e.g. Binary neutron stars or black holes coalescing
  - » In Milky Way sized galaxy
    - – NS-NS merger happens less often than about once every 50 years
    - – for 5.0 M_o BH-BH merger happens less often than about once every 250 years

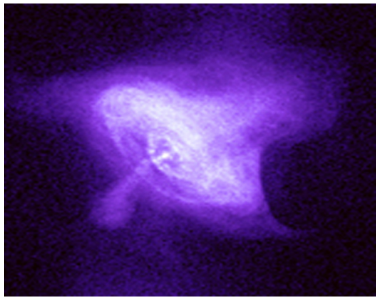


Some science results from LIGO



- Pulsars
  - » Looked for GW signal from ~100 known pulsars
    - – Only get GW emission if source is aspherical
      - Results--pulsars are very spherical
      - Limits on pulsar ellipticity < 10^{-6}
        - » means if bump on 10 km (city sized) pulsar it is <1 cm

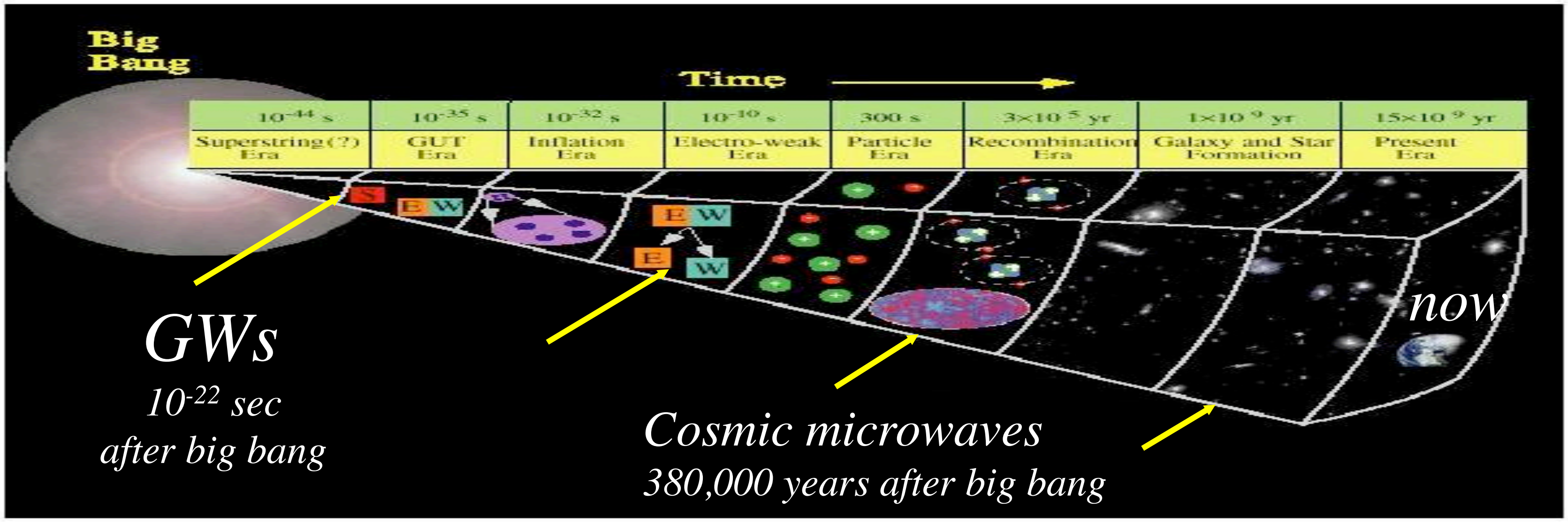
Crab pulsar spindown limit



- Remnant of supernova explosion
  - » In our galaxy, ~6500 light years distant
  - » Neutron star spinning at ~30 Hz
- Slows down by ~38 ns (billionth of second) per day due to emission of energy
- How much of energy loss is into gravitational waves?
- Result from LIGO data--
  - » ~5% of energy loss in spindown goes into GWs

Search GW signal from big bang

- Only possible way to "see" all the way back to the big bang
- Big bang should have produced GWs that fill all of space



- Results published -- GWs from the big bang make up less than 1/100,000 of the energy density in the universe

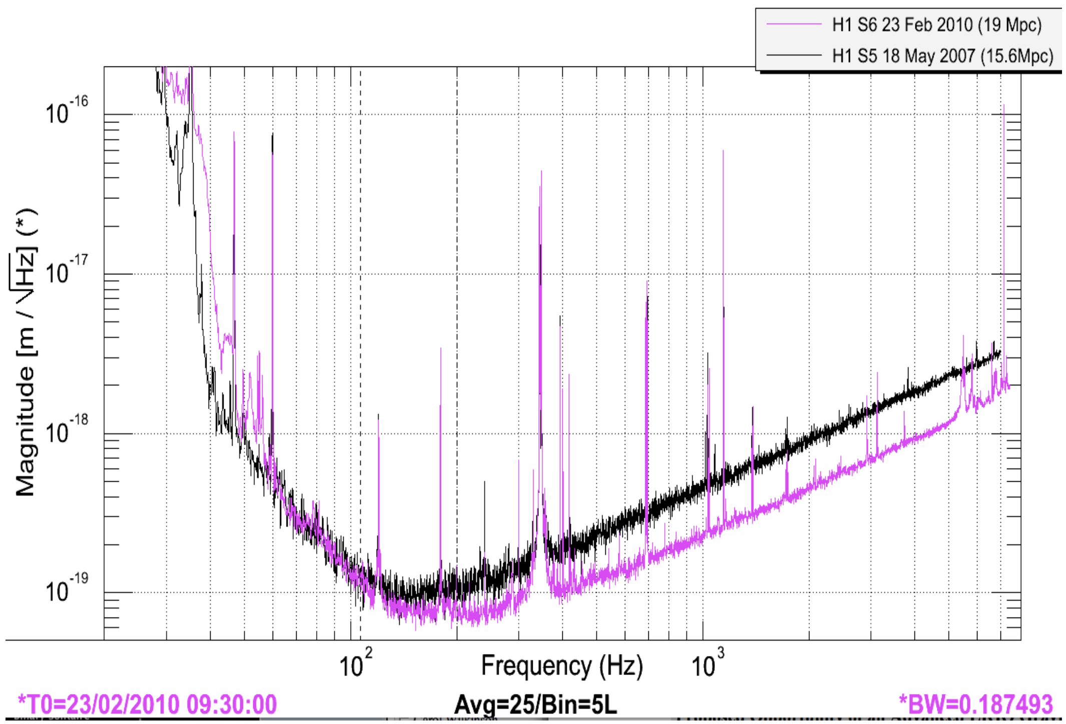
LIGO's evolution after reaching design sensitivity

» **Enhanced LLIGO**

–**July 2009 - October 2010 (S6 science run)**

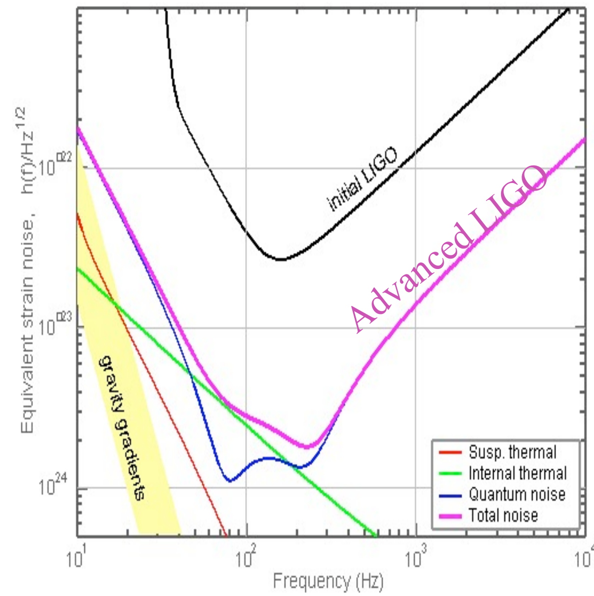
– Key technical step towards Advanced LIGO- new readout, higher laser power, real Advanced LIGO hardware field tested.

– Somewhat improved sensitivity over previous run



Next phase-- gravitational wave astronomy

- **Advanced LIGO--**
  - » Project to improve sensitivity by 10
    - – Sensitive to sources 10x further away
    - – Number of extragalactic sources in range increased by $(10)^3=1000$



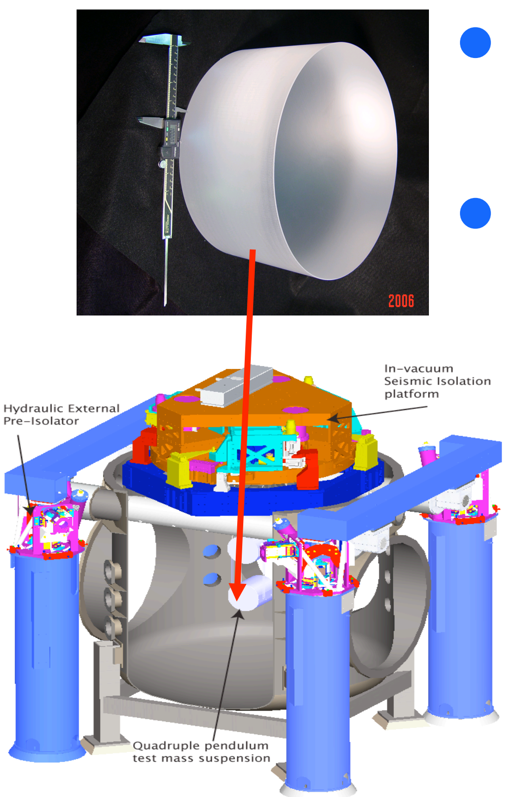
  - » Expect to observe GWs at few/week to few/month rate

1 day of observing with Advanced LIGO equivalent to more than 1 year of initial LIGO

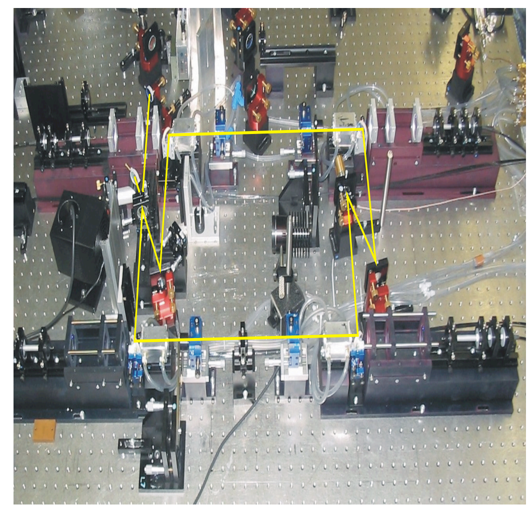
  - » Began project in April 2008; funded by NSF ($205M); UK, Germany, Australia
    - – About 65% complete; construction finished in 2014
    - – 3 new instruments- 1 at Louisiana site, 2 at Hanford site

Advanced LIGO-
improvements from current LIGO

- **Keep initial LIGO “infrastructure” and sites**
  - » Vacuum system (4 km arms), building, roads, etc.
- **Improved technical components including---**

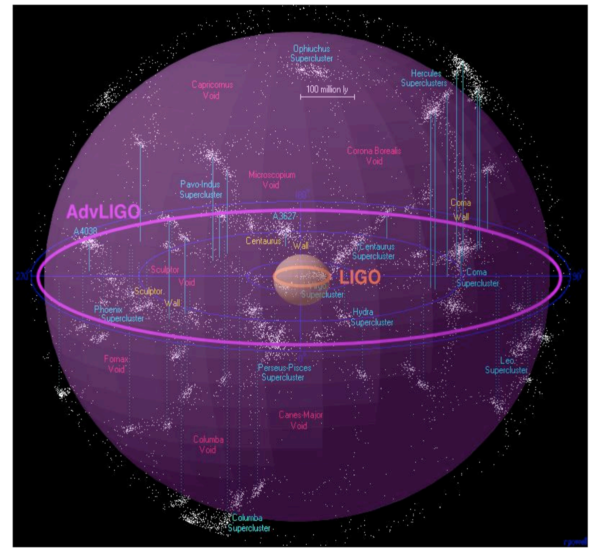


- 20x higher power laser
- Larger, better mirrors
  (to handle increased thermal load)
- Better isolation of mirrors



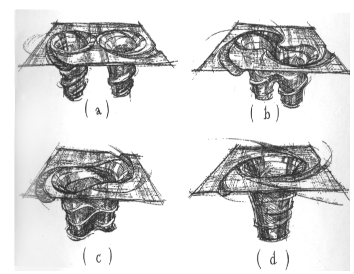
How far will Advanced LIGO "see"
all-sky average

- **Merging neutron star binaries**:



* Initial LIGO: ~50 million light years
* Advanced LIGO: ~500 million light years

hundred's of thousand of galaxies in range



- **Merging black hole binaries**:

* Initial LIGO: Up to 10 M_o, at ~300 million light years
* Advanced LIGO: Up to 50 M_o in most of the universe

When will gravitational waves be discovered??

- Expect by 2016 when with Advanced LIGO we can "observe" 1000 more galaxies than with current LIGO.
- Expected signal rate ~1/week
- ***Then the era of gravitational wave astronomy will begin***

Gravitational wave astronomy ---a new window on the Universe---

GW astronomy needs a global partnership between GW instruments around the globe and other telescopes

- **Will need an earth-spanning instrument to pinpoint direction of GW sources over the whole sky**

- Will permit optical, x-ray, radio telescopes to do follow-up observations of sources of GWs

“We see a GW; point your telescope there; what do you see?”

Towards a global GW "telescope"

- **Why?**
  - » Source location on sky by time-of-arrival triangulation between instruments separated by *continental distances*
- **Goal**- global tetrahedron so can triangulate in all directions
- **Now**-- LIGO, GEO-Germany, Virgo-Italy
  - » Observing together as single array, all in east-west plane
- **The future global array**--
  - » **US**- Adv. LIGO; **Europe**- Adv. Virgo
  - » **Japan**- LCGT; **India ???– important southern node**

- **Sky location**
- **Source polarization**
- **Waveform extraction**
- **Follow-up EM observations**

Global network of interferometers in 2009

LIGO, Virgo and GEO carry out all observing and data analysis as one team since May 2009

The future for ground-based GW interferometers--middle next decade and beyond

- Advanced LIGO will be operating in ~2015; hopefully with good sensitivity in 2016

- Advanced Virgo is bring built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity.

- The Japanese GW community is building LCGT, a 3 km cryogenic interferometer in the Kamioka mine.

- The Indian GW community is seeking funding for a third Advanced LIGO site in India

Advanced VIRGO

- Upgrade of Virgo near Pisa Italy
- Advanced Virgo- 3 km arms
  - » Aims for ~same sensitivity as Advanced LIGO (somewhat better at low frequencies)
  - » Funded by CNRS (France) and INFN (Italy)
  - » Planned to be online ~when Adv. LIGO online
- Status-
  - » Funded
  - » Construction ongoing, slightly behind schedule

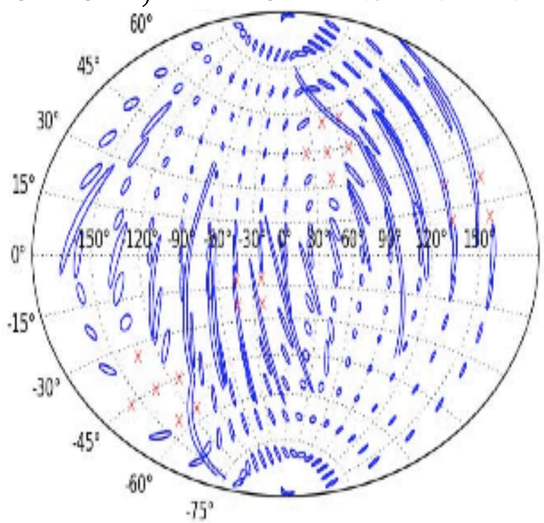
Large Cryogenic Gravitational Wave Telescope (LCGT)

- Site--- Kamioka mine in Japan
- Funded in 2010
- Unique characteristics--
  - » Underground to reduce seismic noise
  - » Cryogenic (mirrors) to reduce thermal noise
- Being built in 2 phases
  - » Phase 1- non-cryogenic, conventional– like initial LIGO. Online in 2016
  - » Cryogenic with higher laser power online 2018

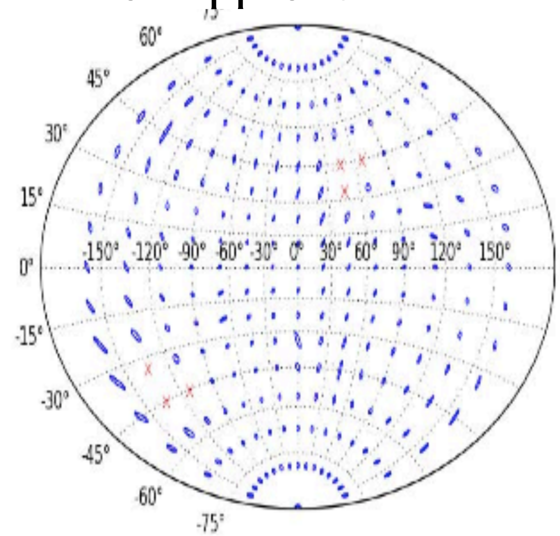
LCGT in Kamioka mine

Towards a Southern site for the the global network

- **1st try---LIGO-Australia**
  - » Idea- Use components from one Advanced LIGO detector from Hanford to assemble a detector in infrastructure provided by Australia
  - » Idea took off; National Science Foundation approved



Adv. LIGO, Adv. Virgo
Without LIGO Australia



With LIGO Australia

Challenge– securing funding (>$200M) in Australia

(Australian economy ~15% of US economy; like $1.5B)

Science excited everyone but poor Australian economy, goal of balanced budget meant no funds

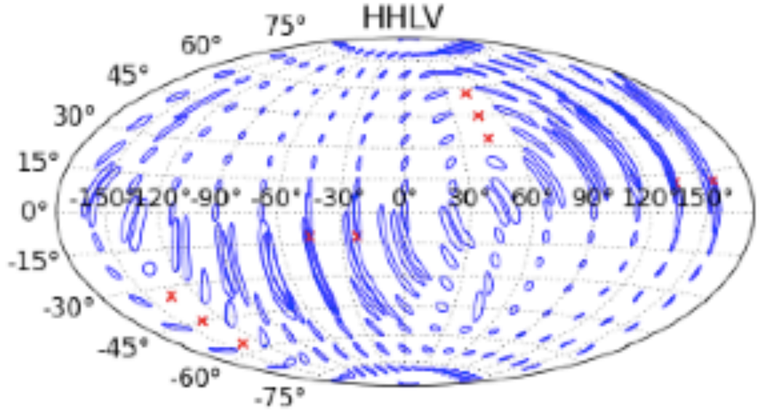
LIGO-India
If not Australia, then India as the Southern site

- Indian GW community has been part of LIGO for years
- Indian interest in partnering in LIGO-Australia (~15%) lead to government awareness of exciting science/ technology of GW instrument
- When LIGO-Australia ended, Indian interest shifted to possibility of full LIGO site there
- Like LIGO Australia, would use an Advanced LIGO interferometer in infrastructure constructed by India
- LIGO-India on short list of inclusion in government's next 5 year plan– while know about funding in next few months
- If it happens, LIGO-India will operate as a third LIGO site as was planned for Australia

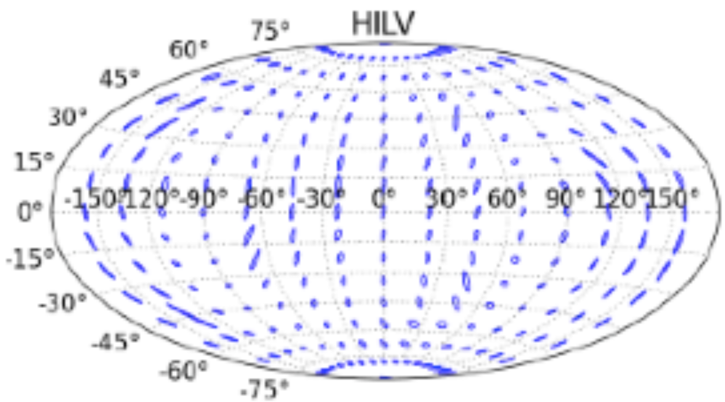
Scientific Benefit of LIGO-India

Determination of source sky position: NS-NS binary inspirals

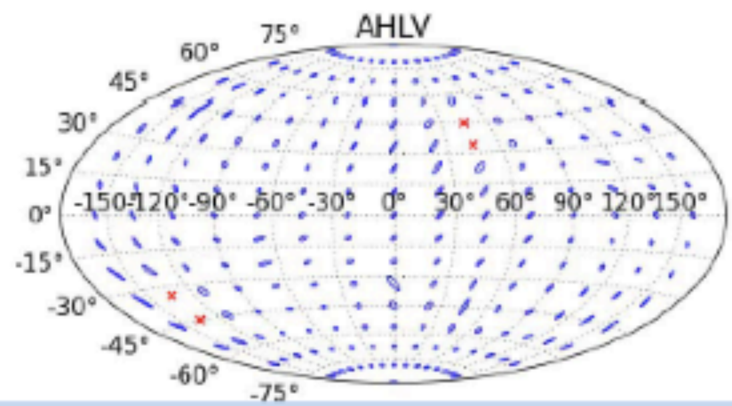
Courtesy:
S. Fairhurst



Original Plan
2 +1 LIGO USA+ Virgo

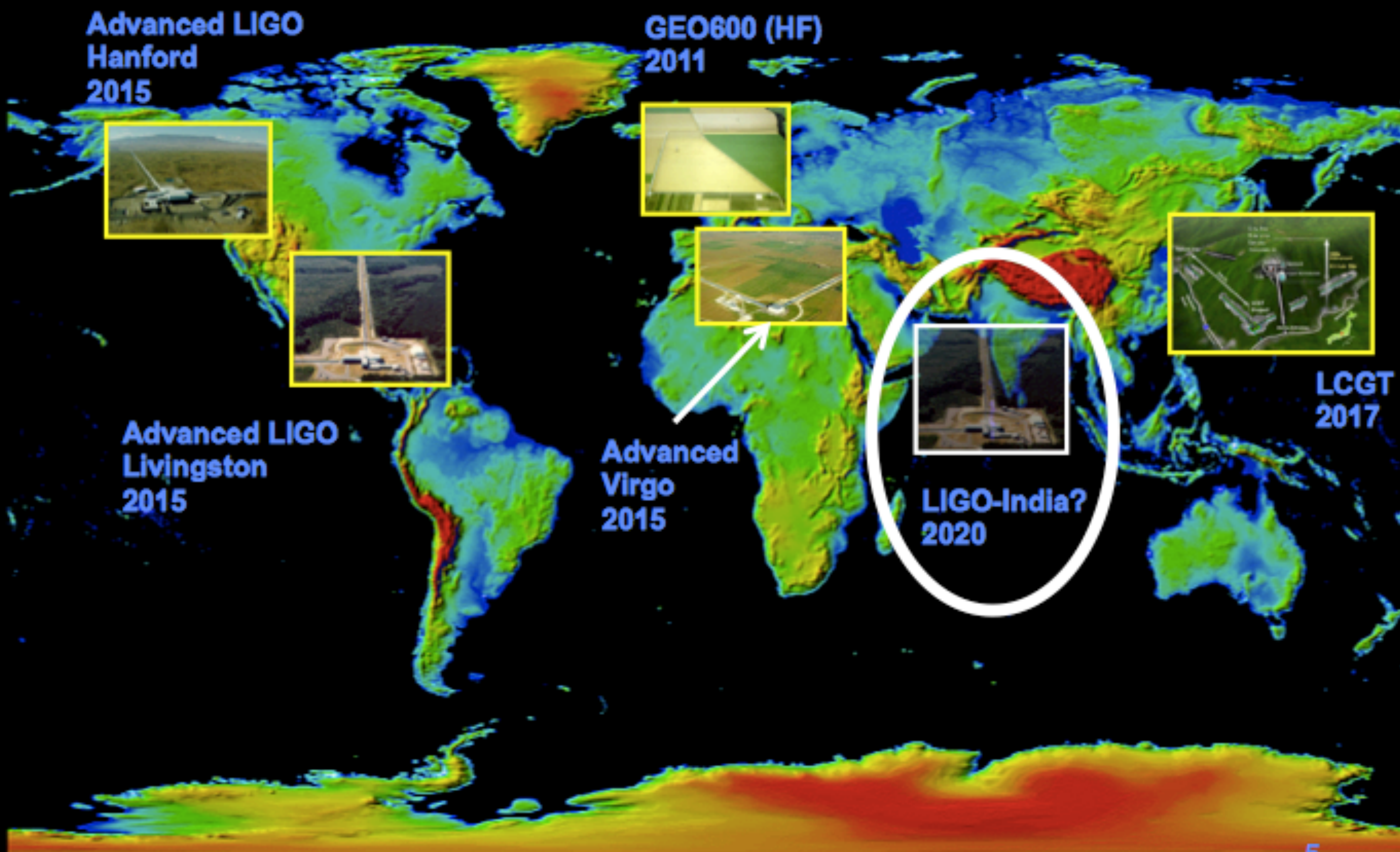


LIGO-India plan

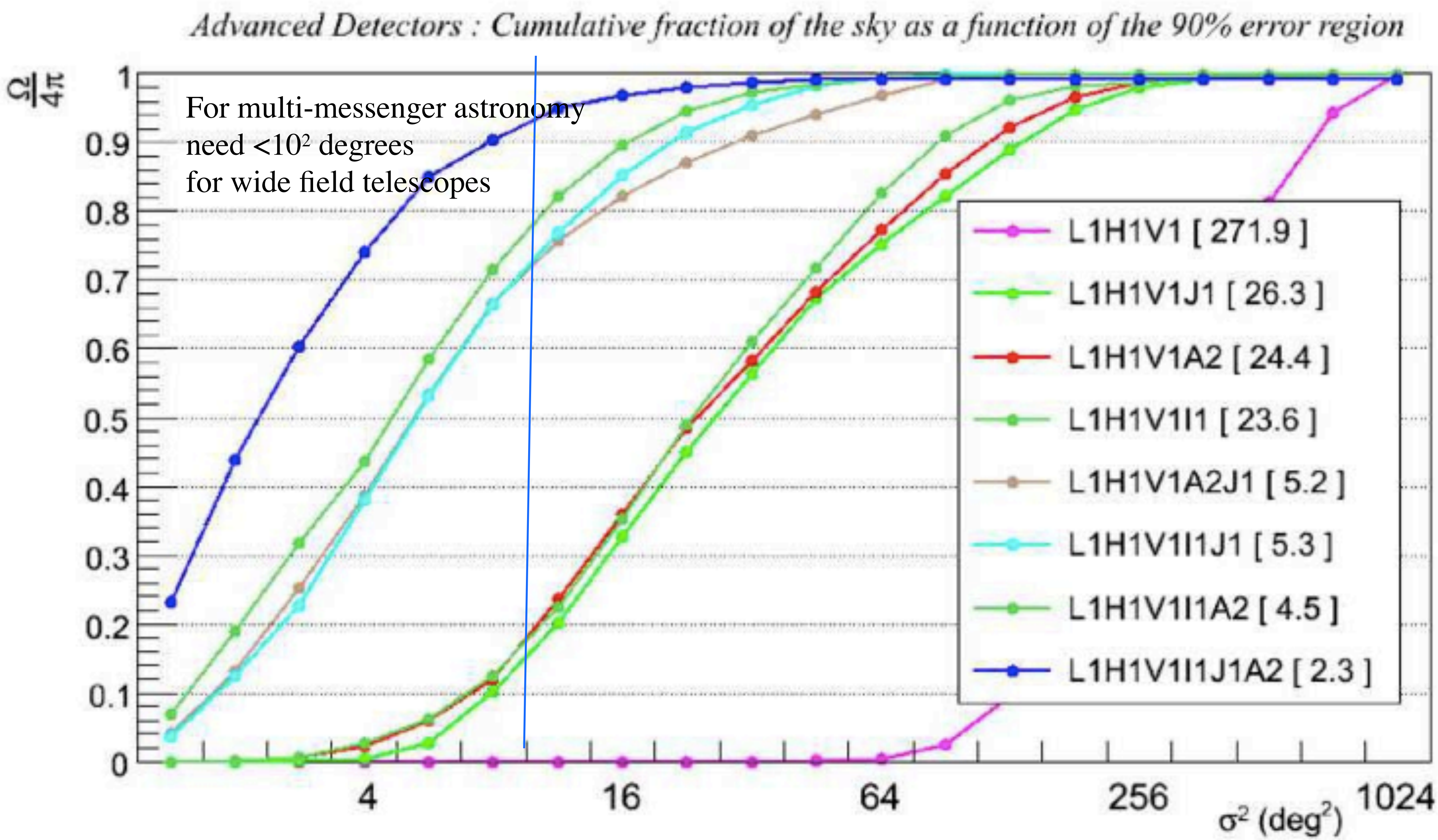


LIGO-Aus plan

The Advanced GW Detector Network



Similar Result for Burst Sources



Example science from global GW telescope

- Multi-messenger astronomy– correlate signals seen in GW with observations in EM (optical, radio, x-ray, gamma), neutrinos to characterize sources of GWs; e.g.
  - » Are short gamma ray bursts NS-NS mergers?
  - » Use merging NS-NS as standard sirens for dark energy measurement—
    - – NS-NS GW emission strength well calculated
    - – Observed GW strength + polarization (orientation of binary) gives distance
    - – Optical observation gives redshift of host galaxy
- In merger phase of neutron state pairs, shape of GW signal is related to nuclear equation of state

Well before the end of this decade we hope to have a world-spanning GW telescope

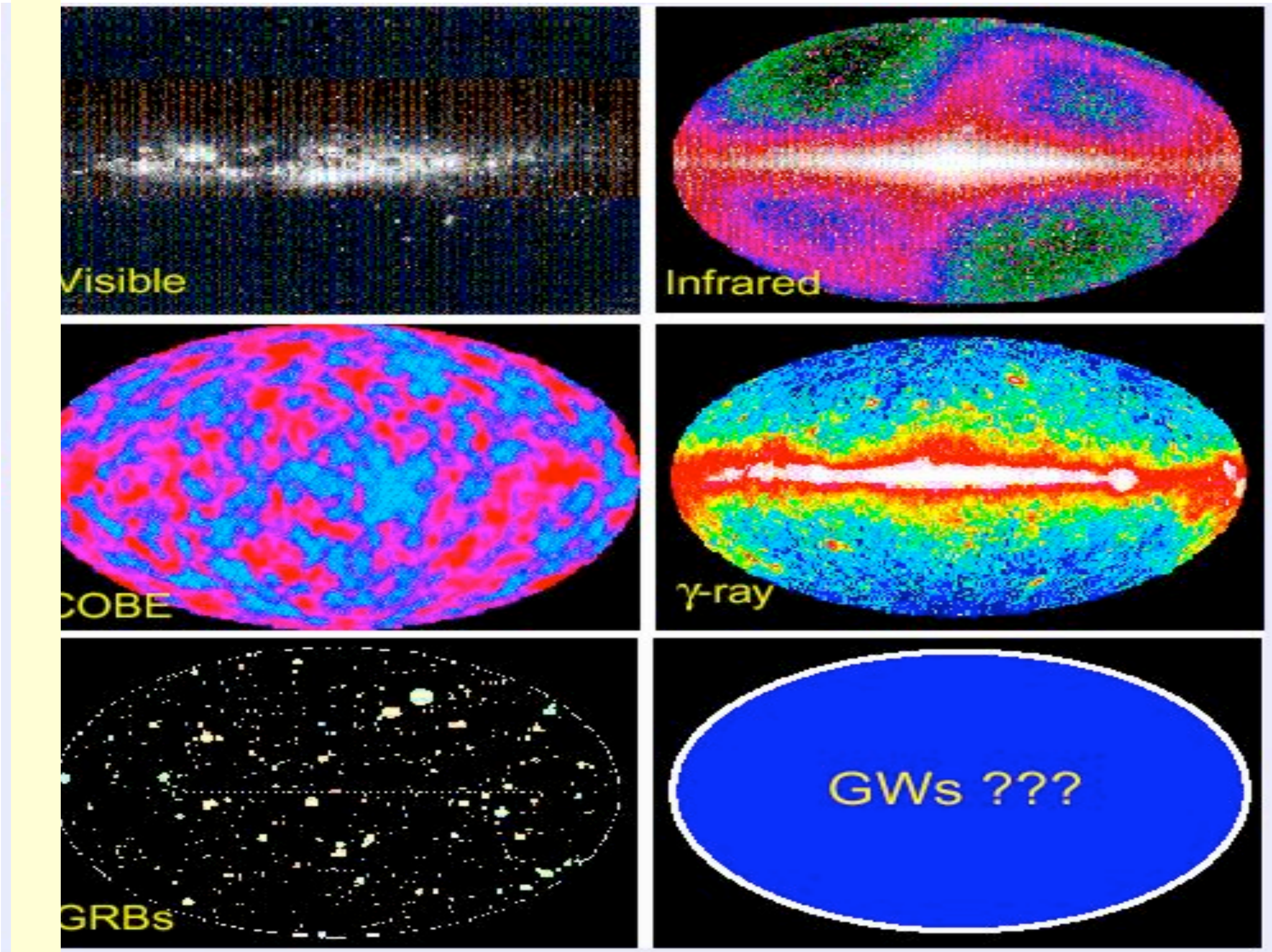
- **Advanced LIGO and Advanced Virgo should be on the air in 2015**

- **LIGO-India and LCGT could be online in 2020**

- **Giving our 1st view of the gravitational wave sky**

- **We expect to learn about some of the must energetic events in the universe (e.g. colliding black holes) and discover new objects and phenomena “out there”**

LIGO poised to give a new view of the heavens, New and deeper insights into nature

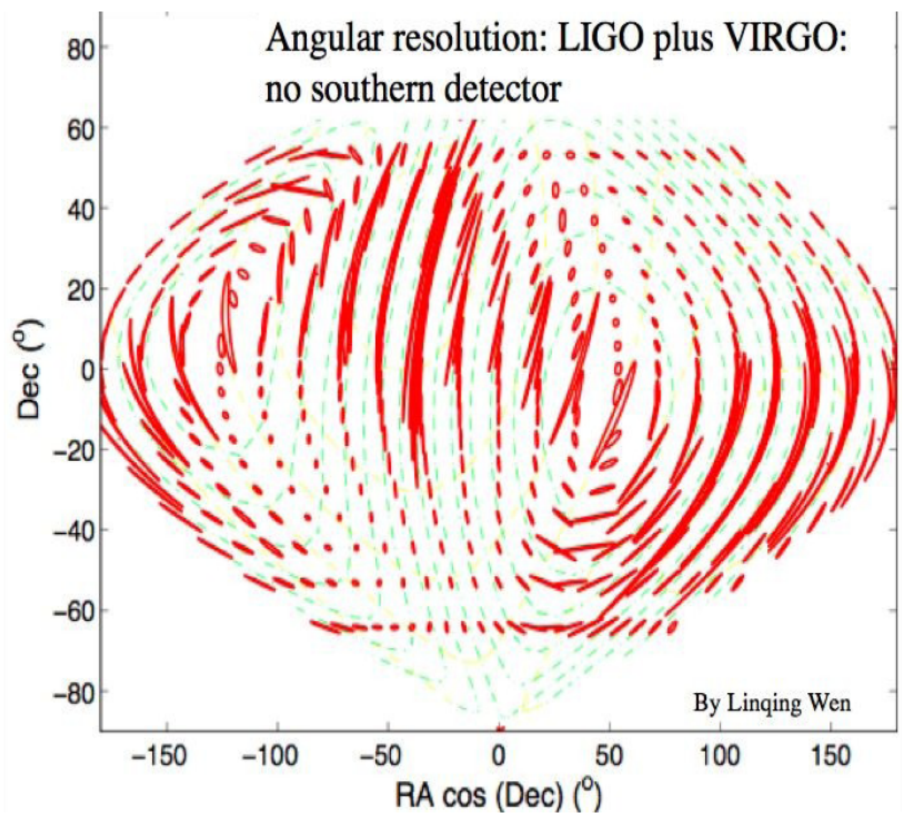


Backup slides

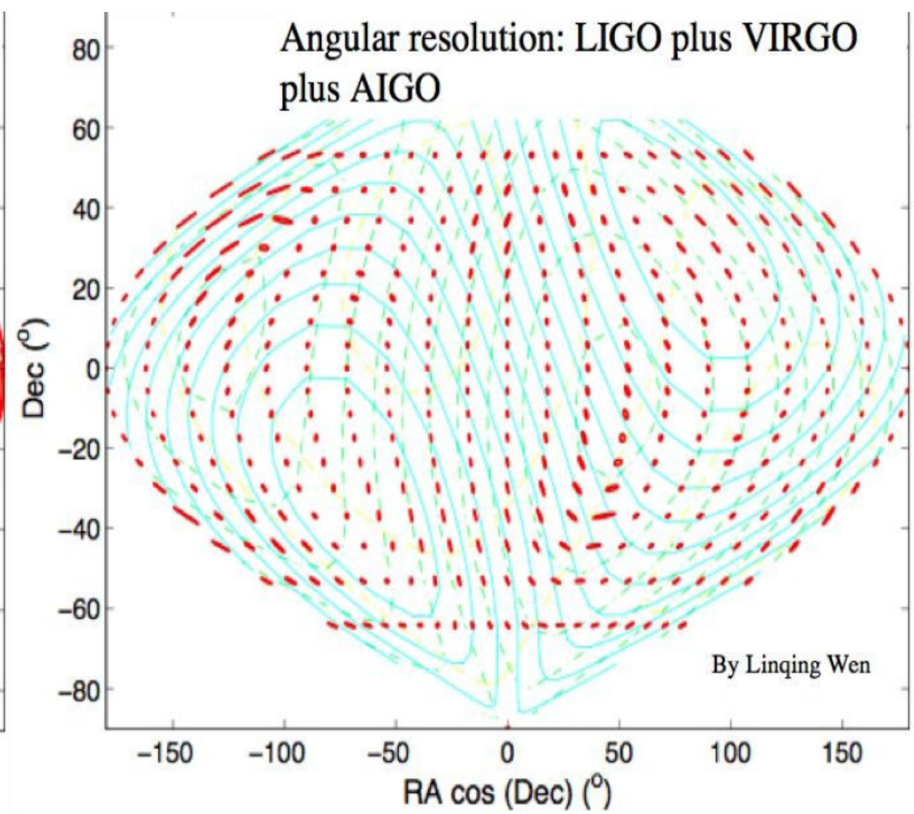
A detector in Australia comparable to LIGO and Virgo would significantly improve network's angular sensitivity

Important for multi-messenger observations using optical, x-ray, radio, gamma ray, neutrino instruments

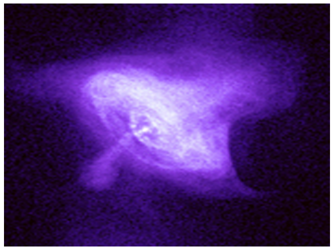
LIGO and Virgo only



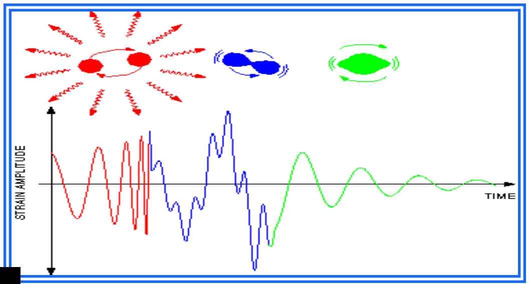
LIGO, VIRGO and AIGO (Australia)



Some cosmic sources of GWs

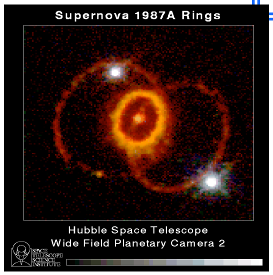


- **Pulsars**---spinning neutron stars

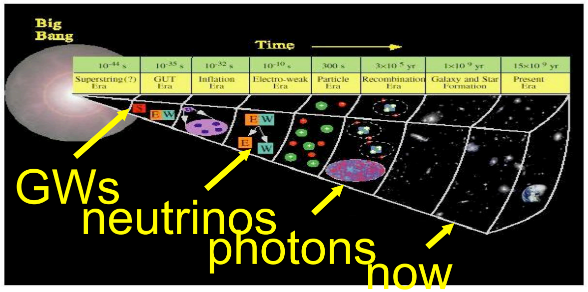


Information is encoded

- **Merging neutron star and black hole binaries** in distant galaxies



- **Huge explosions** --examples
  - **Supernovae**--collapsing core of massive stars
  - **Gamma ray bursts**



- The **big bang**, **cosmic strings** and other phenomena from the early universe

- **The Unexpected-** ?

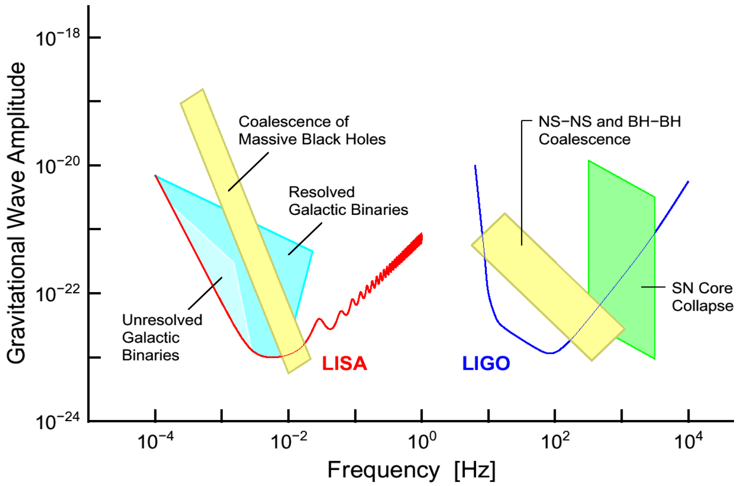
  new instruments see new phenomena!

LISA-- complementing LIGO

Major Caltech and JPL involvement

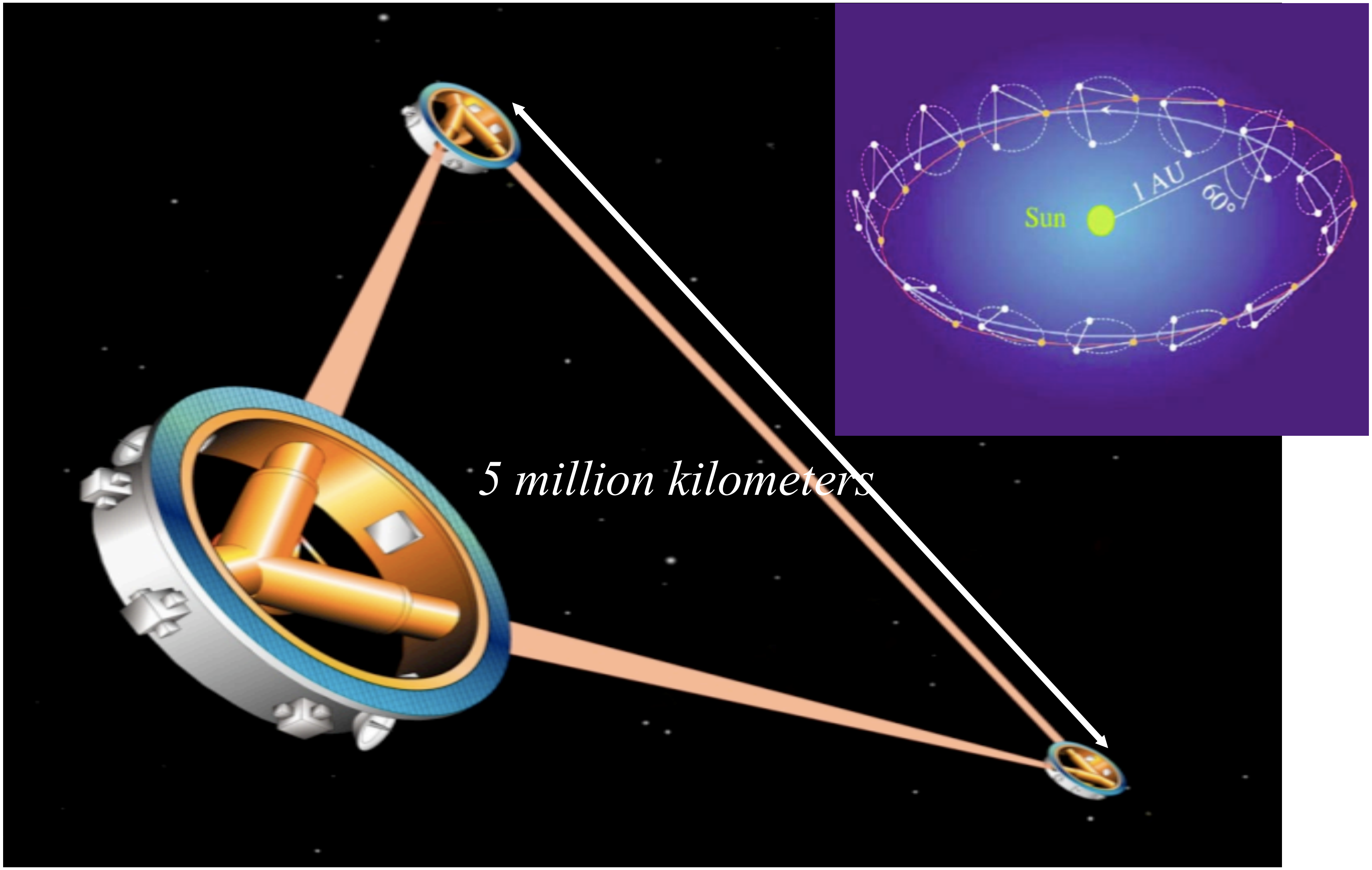
- A GW instrument in space-- 5 million km arms!!!!

- Measure GWs at much lower frequencies than LIGO
  --can only do off the earth



- Will see different kinds of astronomical objects
  - » e.g. merging super-massive black holes from galactic mergers

LISA- launch 2018 by NASA/ESA



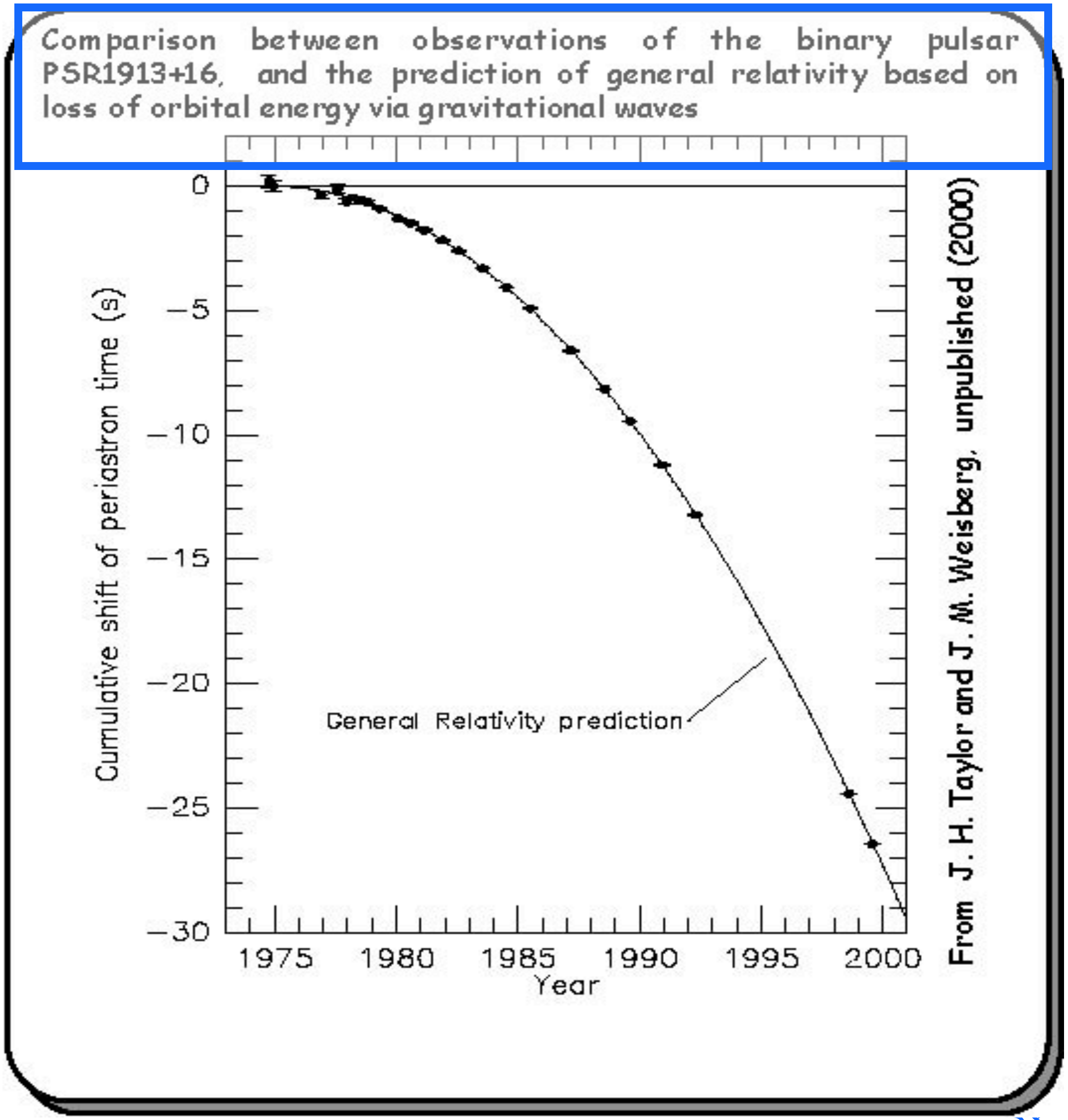
"Indirect" evidence for gravitational waves

Joseph H.Taylor Jr

Russel A. Hulse

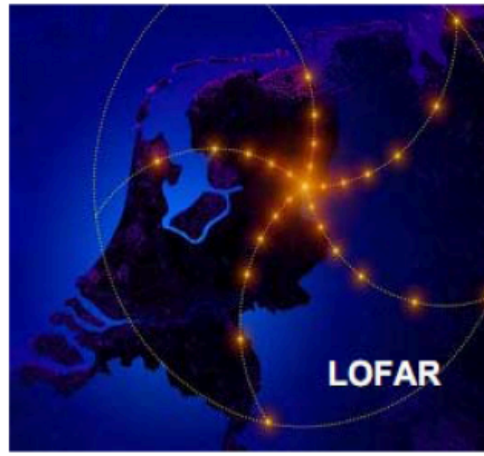
Discovered and Studied Pulsar System PSR 1913 + 16 with Radio Telescope

Won 1993 Nobel Prize

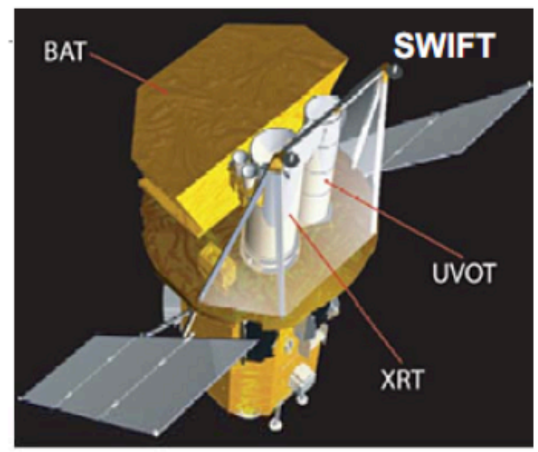


LIGO's current Astrophysics Collaborations

- Neutrino detectors
  - » IceCube and ANTARES MOUs are signed
  - » LV-Super-K MOU on hold
- Wide-field optical follow-ups
  - » All have been approved as part of LOOC-UP
  - » TAROT, QUEST, ROTSE signed
  - » Pi of the Sky, Skymapper, Palomar Transient Factory in process
- NASA satellite missions
  - » RXTE, Swift, Fermi LAT and GBM working through the signature process
  - » Long standing existing MOU with RXTE for Sco-X1 work
- Radio telescopes
  - » Long standing existing MOU with Jodrell Bank
  - » LOFAR working through the signature process
  - » Arecibo, EVLA MOUs under consideration
- Numerical relativity
  - » NINJA2 MOU under development
- *A total of 19 MOUs in force, approved, or pending approval*

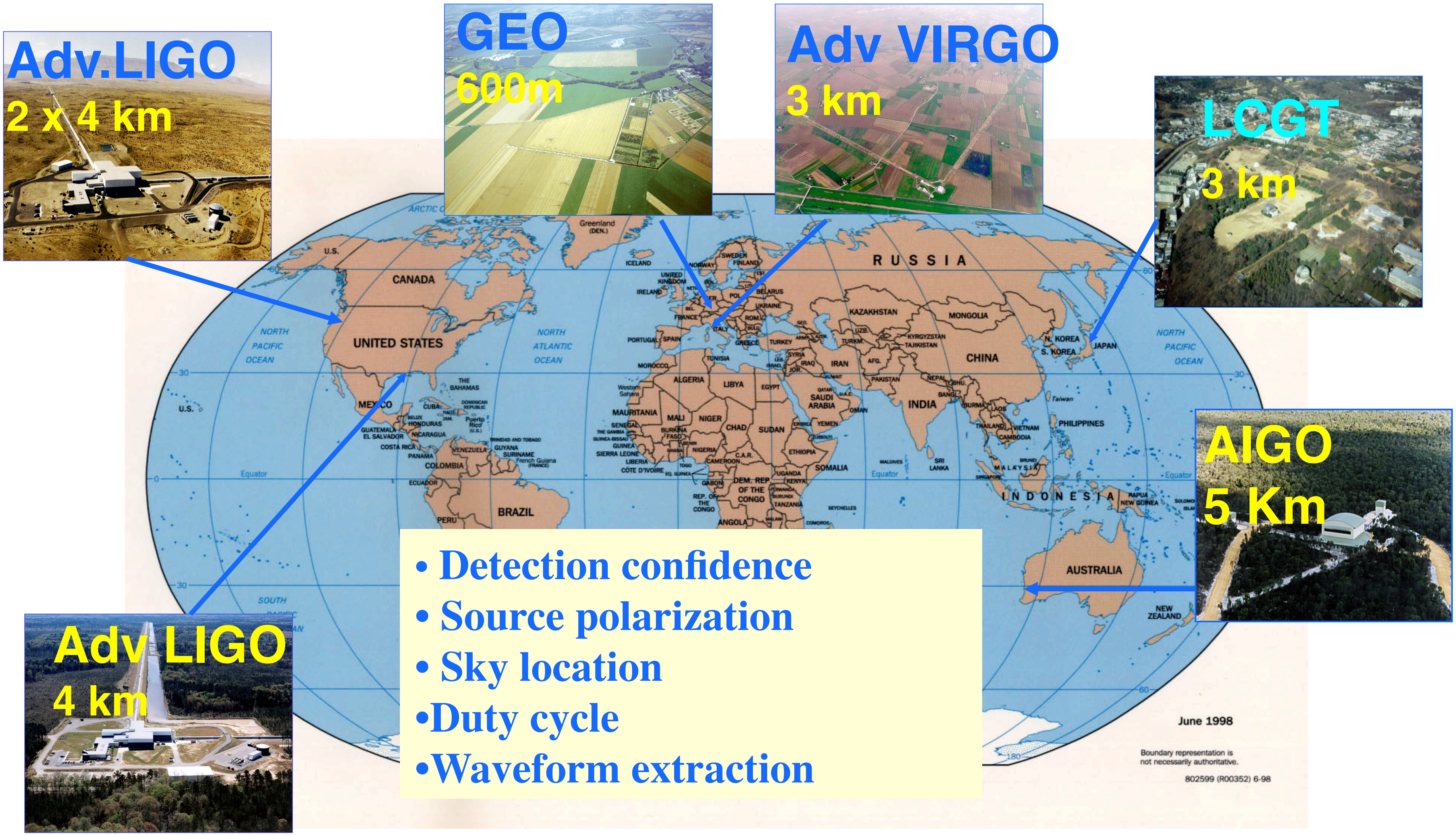


PALOMAR TRANSIENT FACTORY



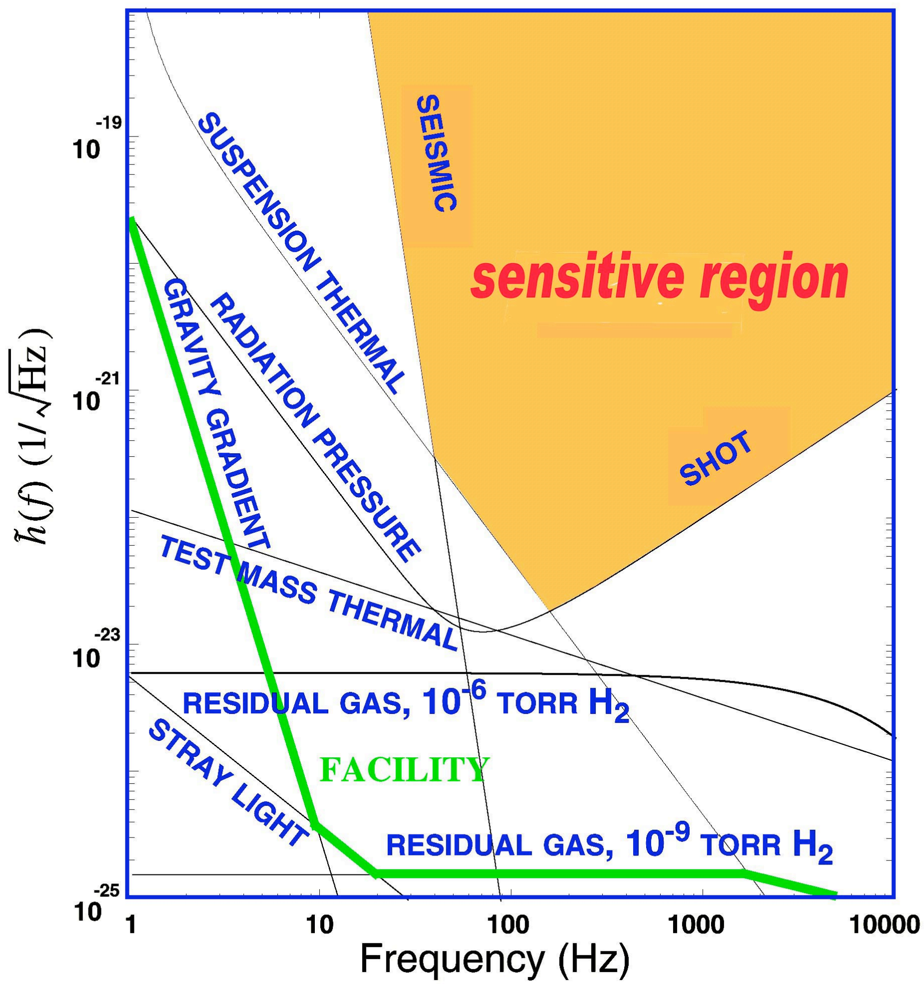
- **Major new involvement with PTF (Corsi)**

A global network of interferometers doing coherent observation-- *next decade and beyond*



- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction

What determines LIGO's Sensitivity?



- Ground motion (Seismic noise) limits low frequencies
  - Pendulum suspensions
- Finite temperature of equipment (thermal noise) limits middle frequencies
  - High Q optics
- Quantum nature of light (Shot Noise fluctuations) limits high frequencies
  - High laser power but more thermal effects
- It has taken years to successfully understand and tame these and other effects

LIGO seismic isolation concept